EFT fit on top quark EW couplings

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Introduction

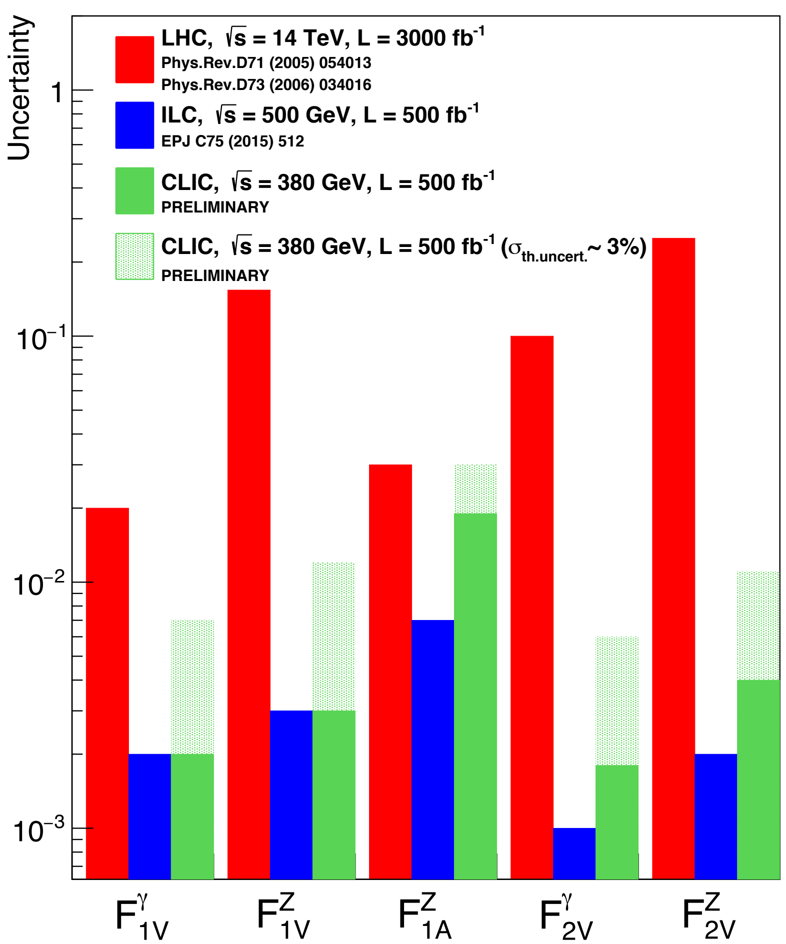
Top quark couplings: form factors

Objective: to study the potential of a global fit in the top EW sector.

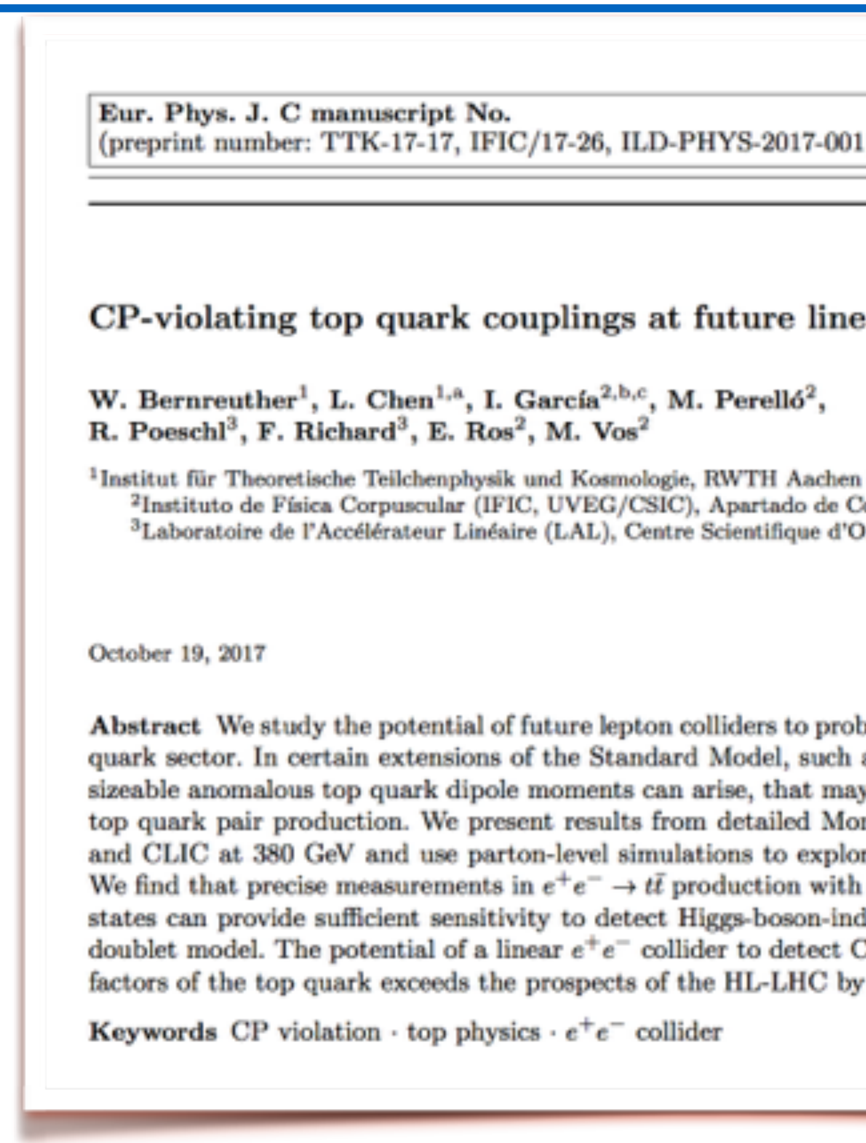
<u>Form-factors</u> $$\Gamma_\mu^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(\underline{F_{1V}^X(k^2)} + \gamma_5 \underline{F_{1A}^X(k^2)}\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu \left(i\underline{F_{2V}^X(k^2)} + \gamma_5 \underline{F_{2A}^X(k^2)}\right)\right\}$$

CP Conserving **CPV**

CLIC baseline document (arXiv:1608.07537) and arXiv:1505.06020



arXiv:1710.06737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CP-violating top quark couplings at future linear e^+e^- colliders

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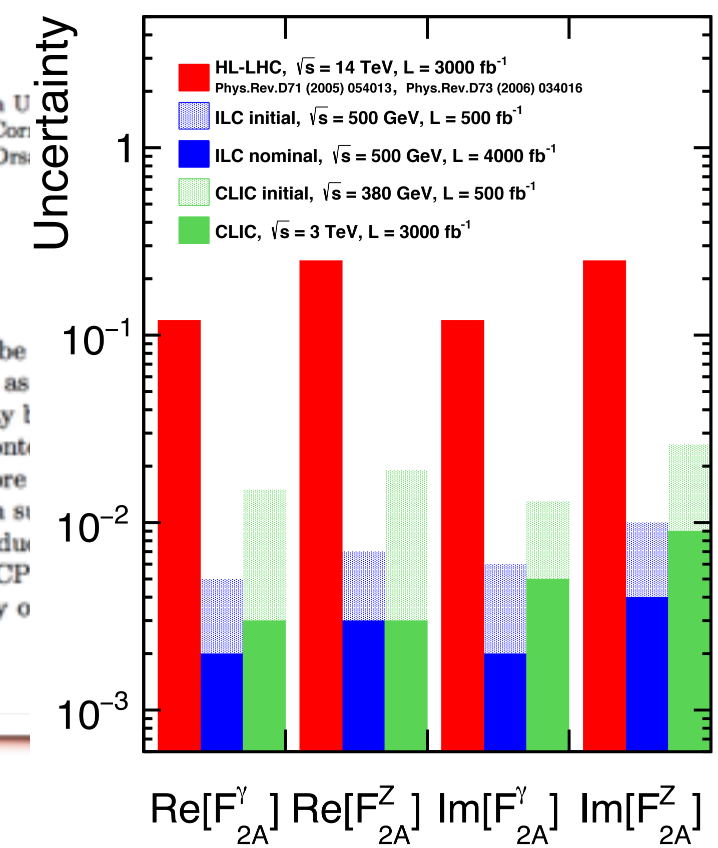
October 19, 2017

Abstract We study the potential of future lepton colliders to probe quark sector. In certain extensions of the Standard Model, such as sizeable anomalous top quark dipole moments can arise, that may l top quark pair production. We present results from detailed Mont and CLIC at 380 GeV and use parton-level simulations to explore We find that precise measurements in $e^+e^- \to t\bar{t}$ production with s states can provide sufficient sensitivity to detect Higgs-boson-indu doublet model. The potential of a linear e^+e^- collider to detect CP factors of the top quark exceeds the prospects of the HL-LHC by o

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



Top quark couplings: EFT

Effective Field Theory

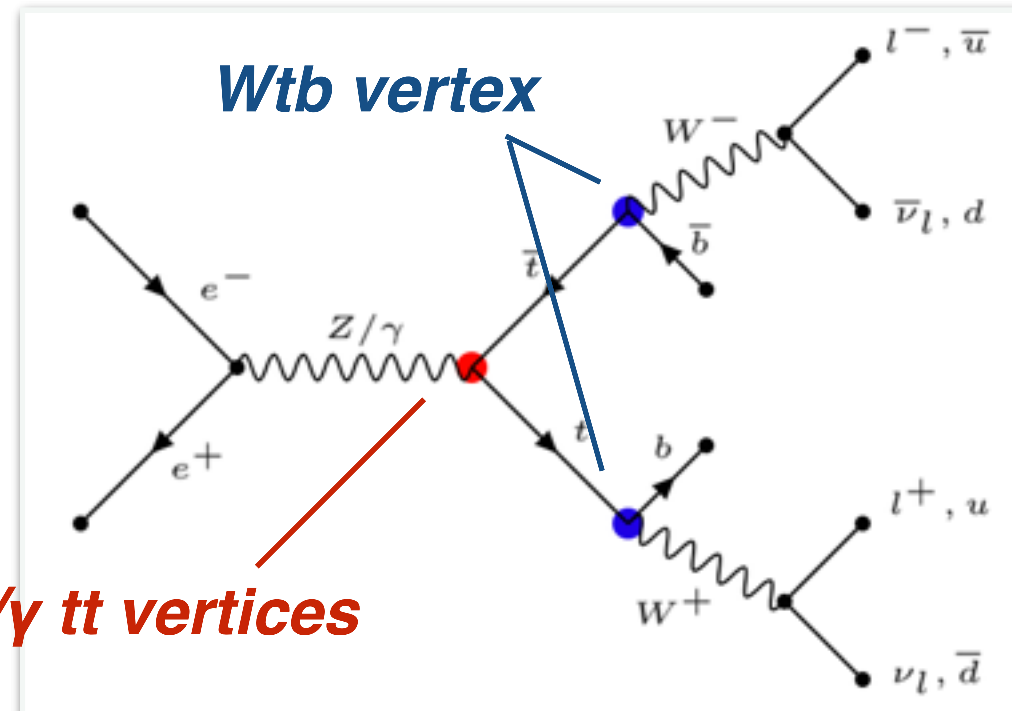
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

See *"EFT fromalism for top physics"* from C. Grojean on Tuesday for a theory motivation

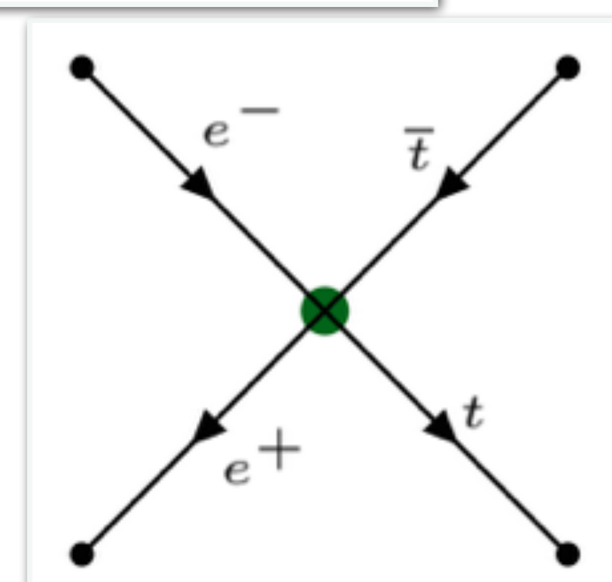
dim-6 operators on tt production and decay…

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

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



Contact interactions



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

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

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

Different EFT basis

Transformation between effective operators and form-factors:

$$F^Z_{1,V} - F^{Z,SM}_{1,V} = \frac{1}{2}\left(\underline{C^{(3)}_{\varphi Q} - C^{(1)}_{\varphi Q} - C_{\varphi t}}\right)\frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2}\underline{C^V_{\varphi q}}\frac{m_t^2}{\Lambda^2 s_W c_W}$$

$$F^Z_{1,A} - F^{Z,SM}_{1,A} = \frac{1}{2}\left(\underline{-C^{(3)}_{\varphi Q} + C^{(1)}_{\varphi Q} - C_{\varphi t}}\right)\frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2}\underline{C^A_{\varphi q}}\frac{m_t^2}{\Lambda^2 s_W c_W}$$

$$F^Z_{2,V} = \left(\underline{\mathrm{Re}\{C_{tW}\}c_W^2 - \mathrm{Re}\{C_{tB}\}s_W^2}\right)\frac{4m_t^2}{\Lambda^2 s_W c_W} = \mathrm{Re}\{\underline{C_{uZ}}\}\frac{4m_t^2}{\Lambda^2}$$

$$F^\gamma_{2,V} = \left(\underline{\mathrm{Re}\{C_{tW}\} + \mathrm{Re}\{C_{tB}\}}\right)\frac{4m_t^2}{\Lambda^2} = \mathrm{Re}\{\underline{C_{uA}}\}\frac{4m_t^2}{\Lambda^2}$$

$$[F^Z_{2,A}, F^\gamma_{2,A}] \propto \underline{[\mathrm{Im}\{C_{tW}\}, \mathrm{Im}\{C_{tB}\}]}$$

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

10 operators in the global fit:

- 4 CP-conserving ttX vertices
- 2 CP-violating ttX vertices
- 4 contact interactions

Contact interactions:

$$C^V_{lq} \equiv C_{lu} + C^{(1)}_{lq} - C^{(3)}_{lq} \qquad C^V_{eq} \equiv C_{eu} + C_{eq}$$

$$C^A_{lq} \equiv C_{lu} - C^{(1)}_{lq} + C^{(3)}_{lq} \qquad C^A_{eq} \equiv C_{eu} - C_{eq}$$

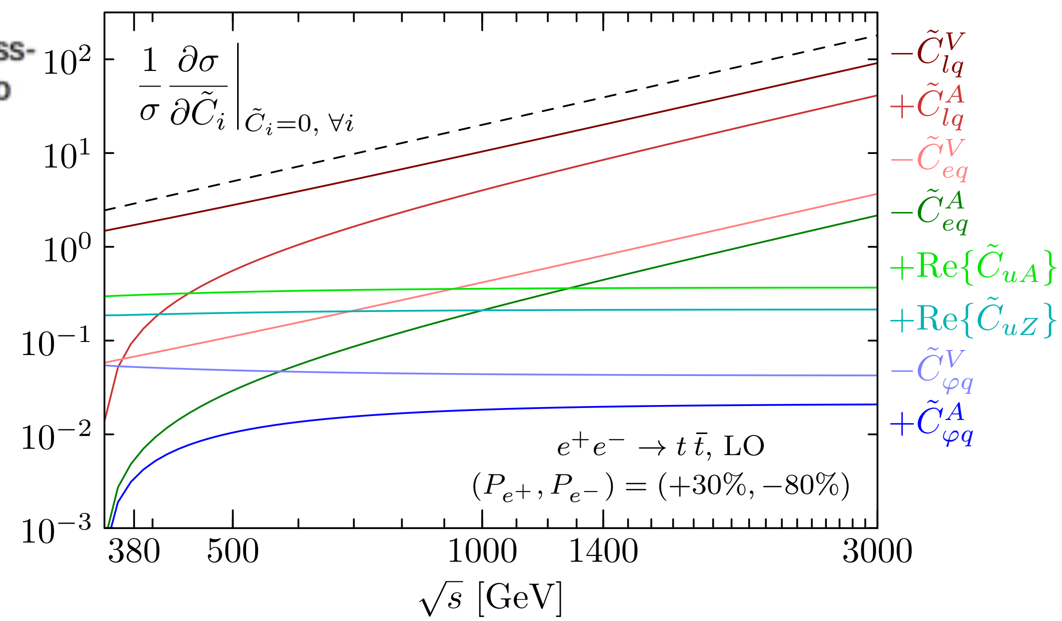
Observables

Observables sensitivity: A_{FB} + cross-section

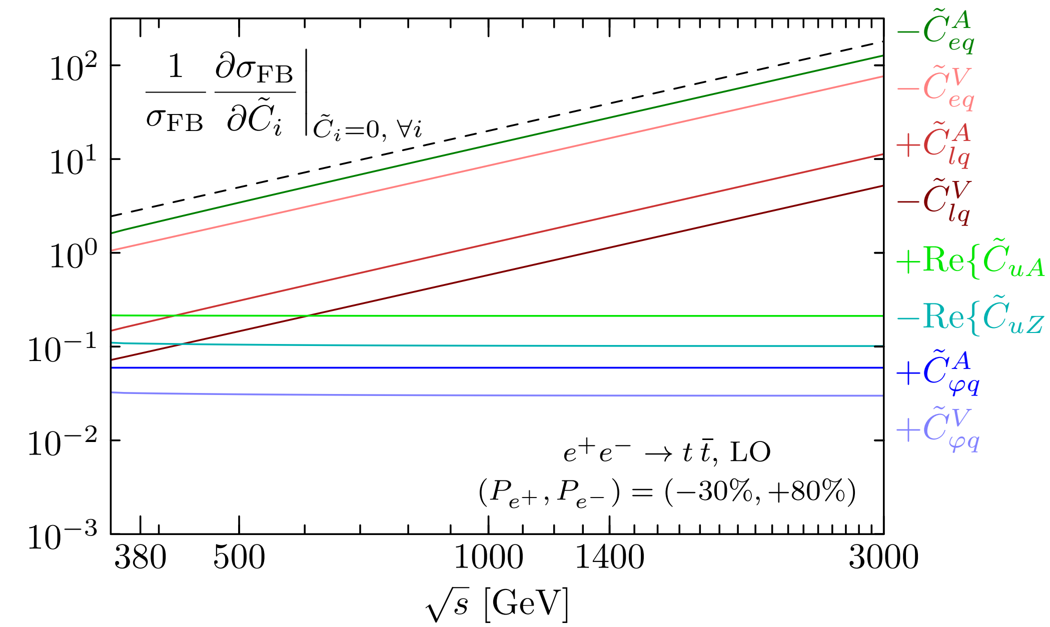
$e^+e^- \to t\,\bar{t}$, LO **Durieux, Perelló, Vos, Zhang, to be published**

Sensitivity:
Relative change in cross-section due to non-zero operator coefficient
Δσ (C) / σ / ΔC

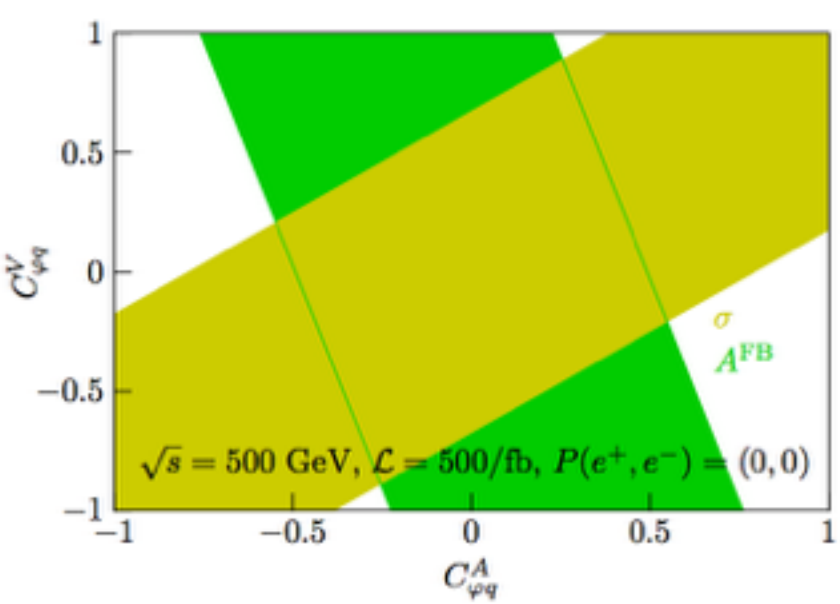
Cross-section

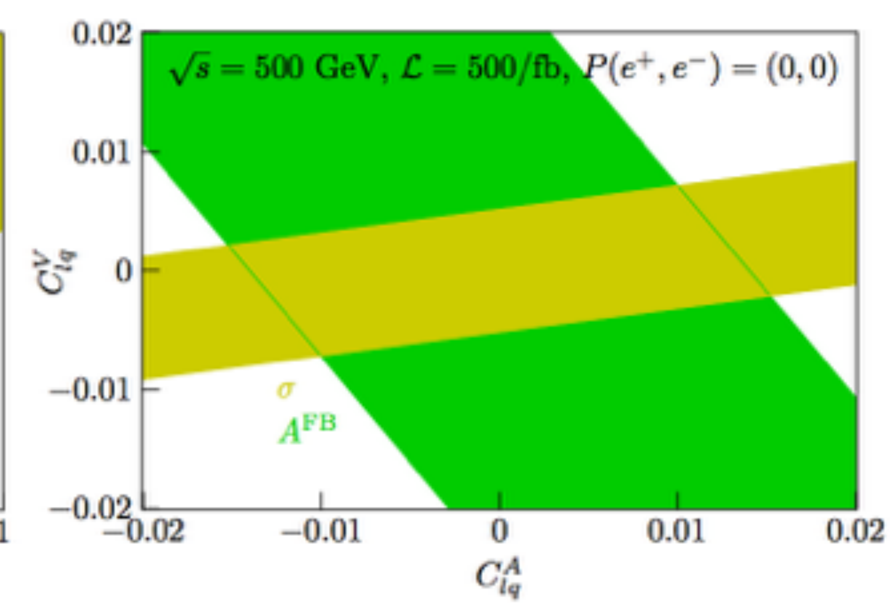


Forward-backward asymmetry



Nice **complementarity** between Afb and cross-section to **disentangle vector** and **axial operators**.





Observables sensitivity: A_{FB} + cross-section

$e^+e^- \to t\,\bar{t}$, LO **Durieux, Perelló, Vos, Zhang, to be published**

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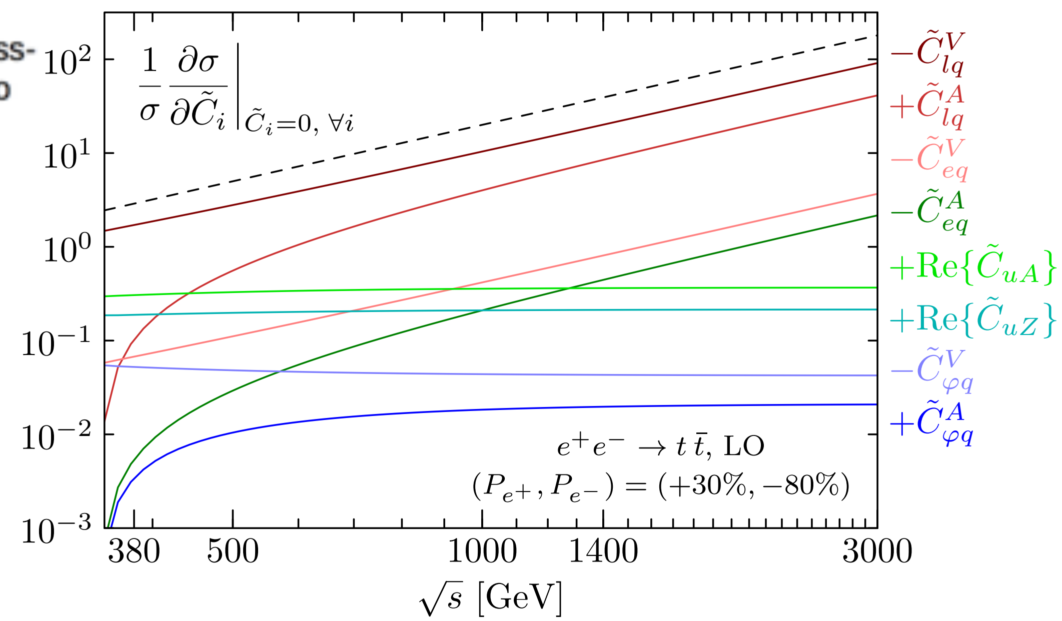
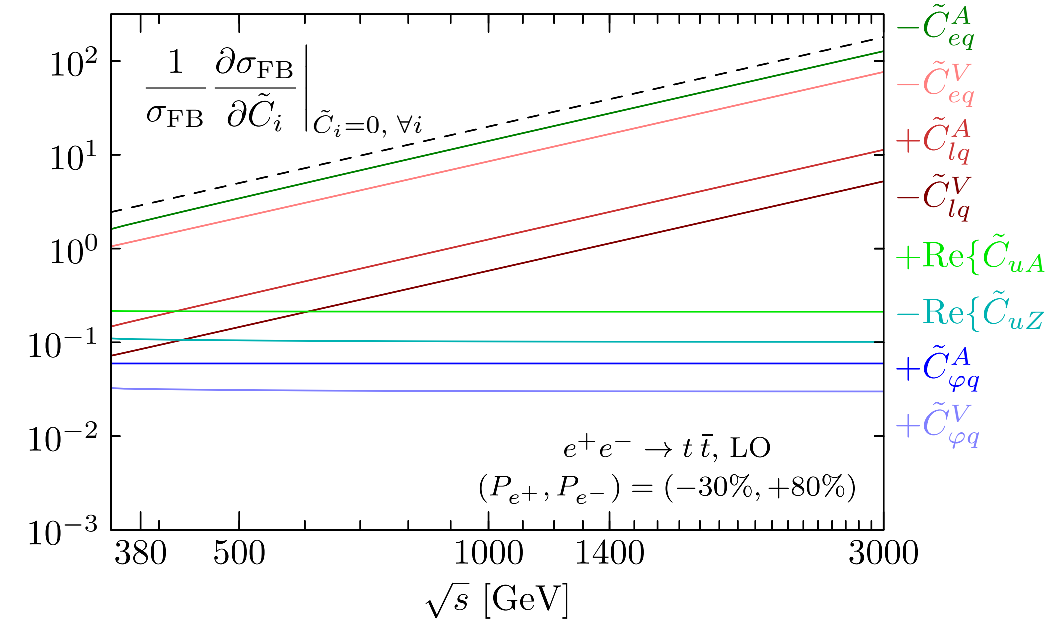
$\Delta\sigma$ (C) / σ / ΔC

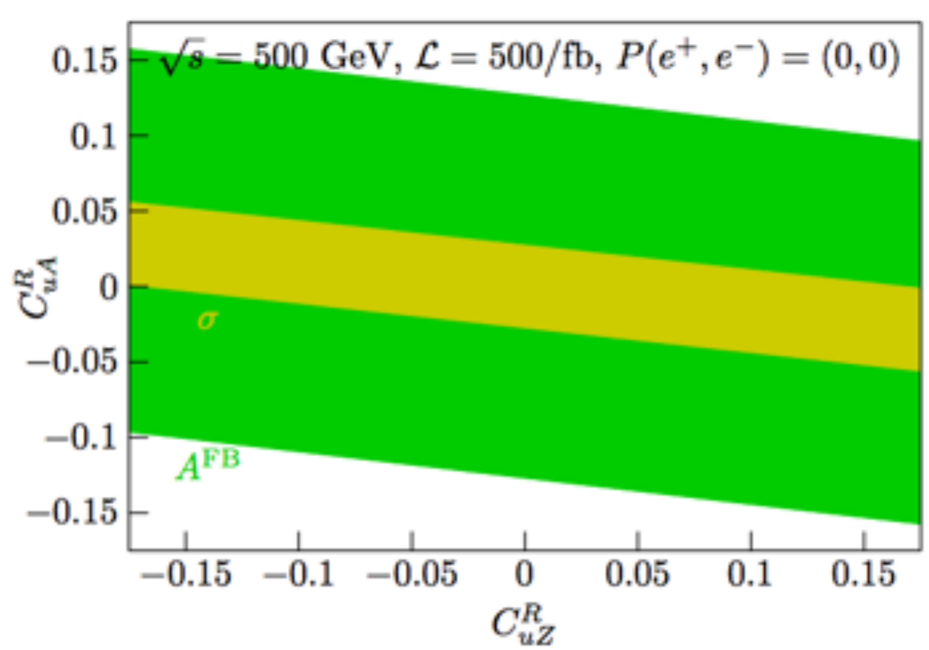
Cross-section

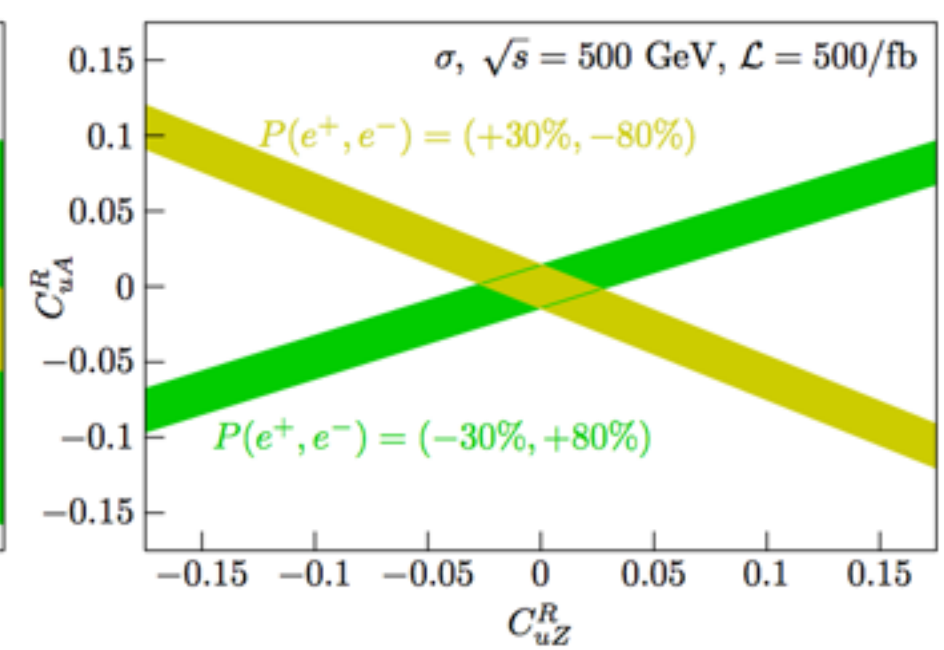


Forward-backward asymmetry



Role of beams polarization:





Observables sensitivity: A_{FB} + cross-section

$e^+e^- \to t\,\bar{t}$, LO **Durieux, Perelló, Vos, Zhang, to be published**

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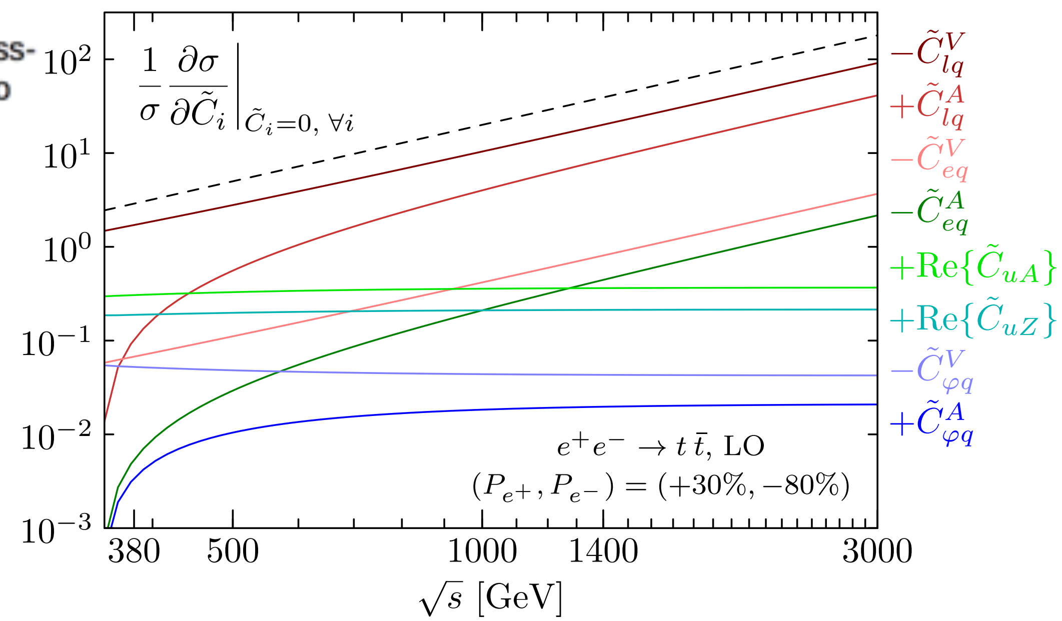
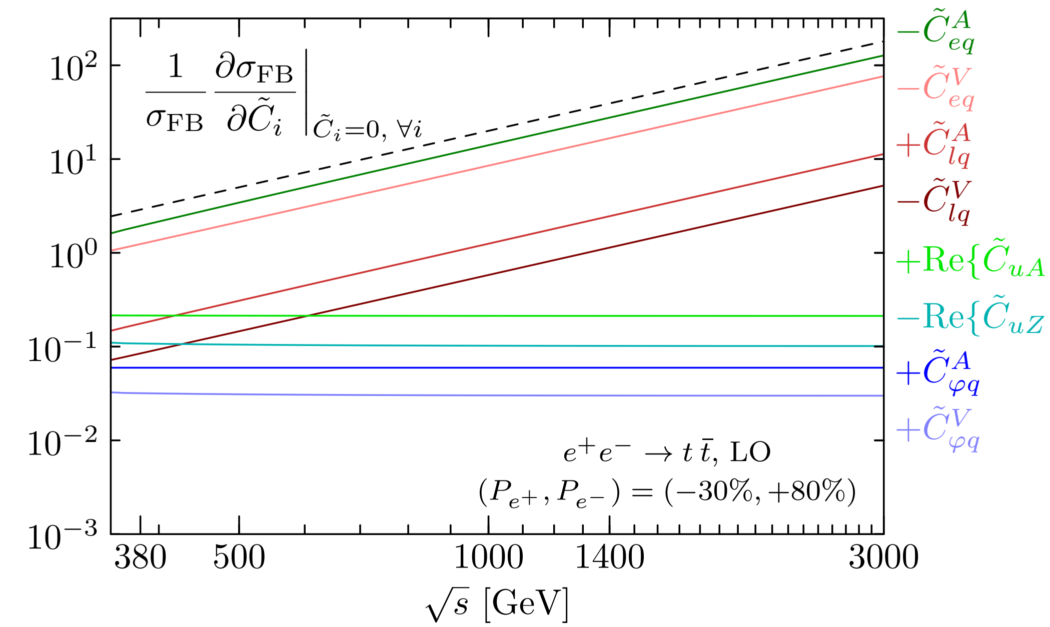


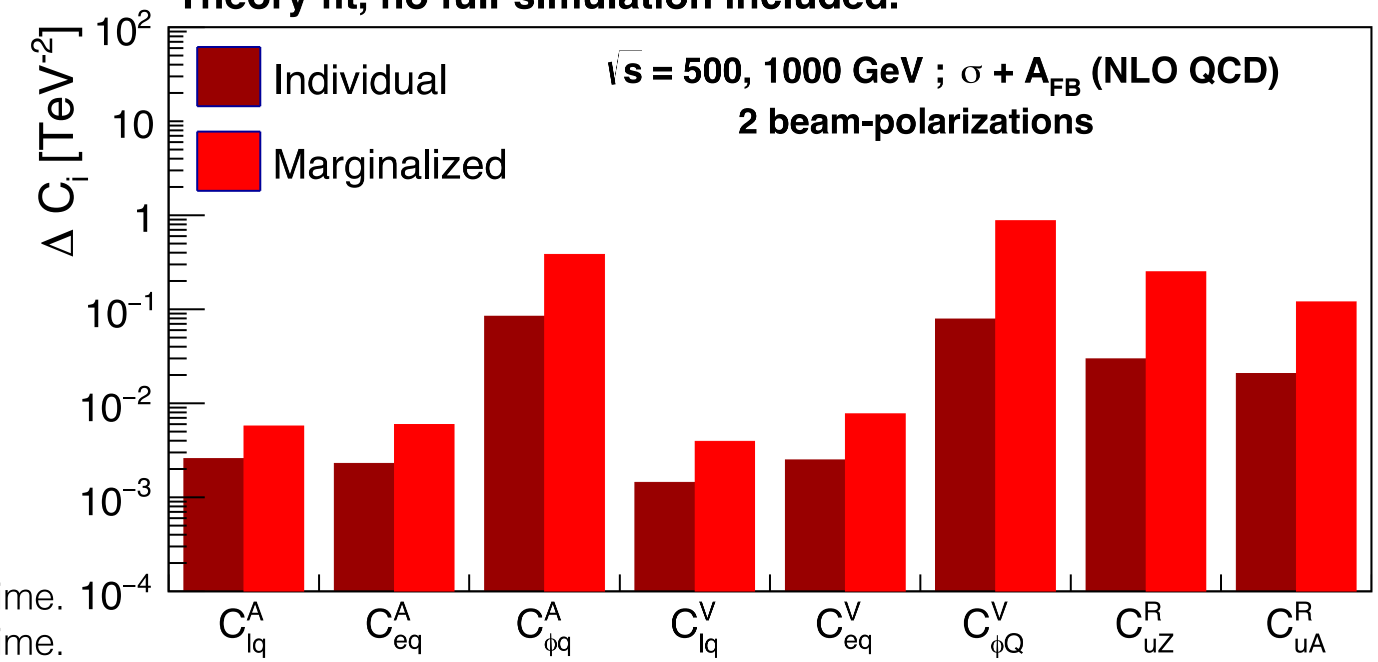
Forward-backward asymmetry



Nothing can be done with only one energy point!

- At least we need **one low energy with high statistics for the vertices**, and **one high energy for the contact interactions.**

Theory fit, no full-simulation included.



Need for new observables to reduce the difference between individual and marginalized fits

Individual: assuming variation in only 1 parameter each time.
Marginalized: assuming variation in all the parameters at the same time.

CPV observables in the global fit **arXiv:1710.06737**

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

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

$$\begin{aligned} t\ \bar{t} \quad &\rightarrow \quad \ell^+(\mathbf{q}_+) + \nu_\ell + b + \overline{X}_{\mathrm{had}}(\mathbf{q}_{\bar{X}}) \\ t\ \bar{t} \quad &\rightarrow \quad X_{\mathrm{had}}(\mathbf{q}_X) + \ell^-(\mathbf{q}_-) + \bar{\nu}_\ell + \bar{b} \end{aligned}$$

- **CP-odd observables** are defined with the **four momenta available in tt semi-leptonic decay channel**

$$\begin{aligned} \mathcal{O}_+^{Re} &= (\hat{\mathbf{q}}_{\bar{X}} \times \hat{\mathbf{q}}_+^*) \cdot \hat{\mathbf{p}}_+ \,, \\ \mathcal{O}_+^{Im} &= -[1 + (\frac{\sqrt{s}}{2m_t} - 1)(\hat{\mathbf{q}}_{\bar{X}} \cdot \hat{\mathbf{p}}_+)^2]\hat{\mathbf{q}}_+^* \cdot \hat{\mathbf{q}}_{\bar{X}} + \frac{\sqrt{s}}{2m_t}\hat{\mathbf{q}}_{\bar{X}} \cdot \hat{\mathbf{p}}_+ \hat{\mathbf{q}}_+^* \cdot \hat{\mathbf{p}}_+ \end{aligned}$$

- The way to **extract** the **CP-violating form factor** is to construct **asymmetries sensitive to CP-violation effects**

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

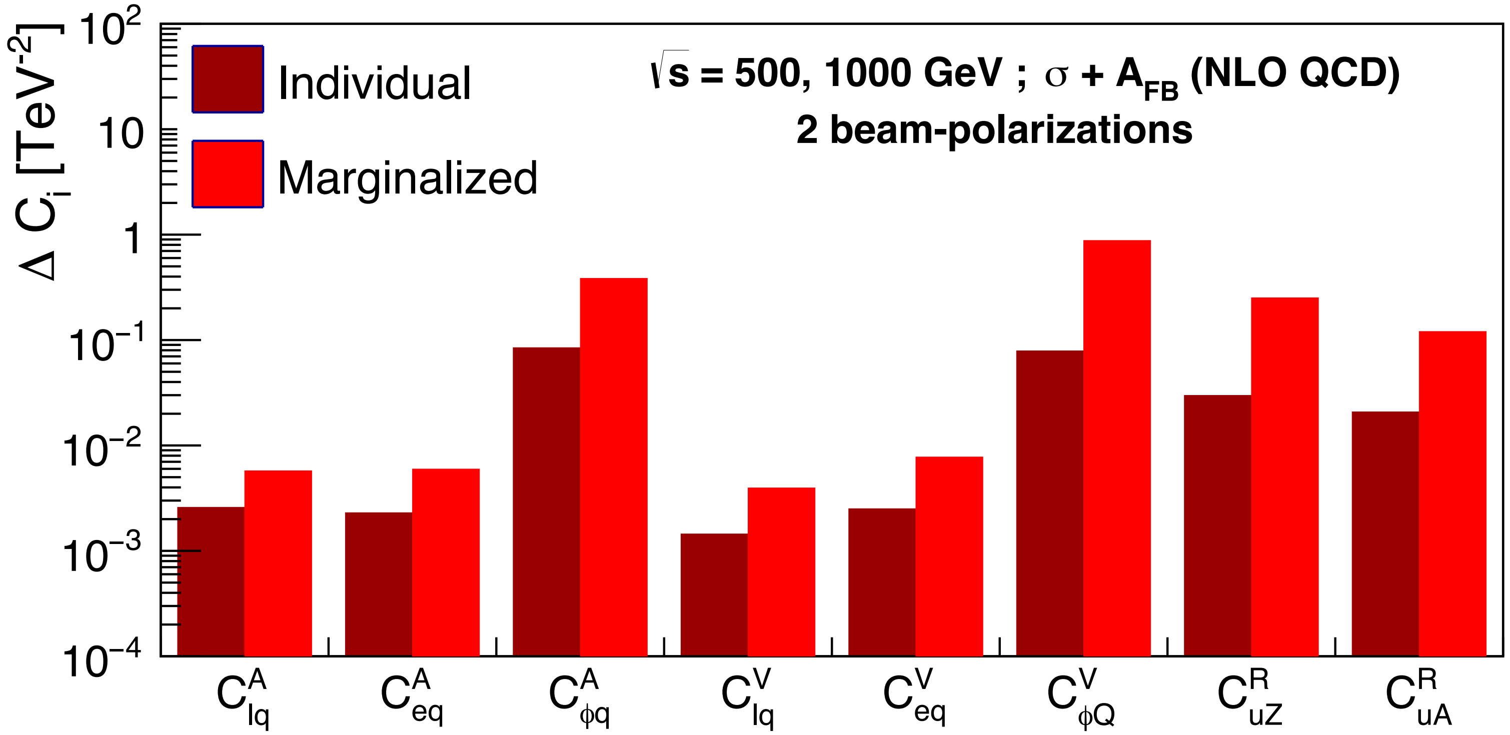
$$\mathcal{A}^{Im} = \langle \mathcal{O}_+^{Im} \rangle - \langle \mathcal{O}_-^{Im} \rangle = \boxed{\tilde{c}_\gamma(s)} \mathrm{Im}F_{2A}^\gamma + \boxed{\tilde{c}_Z(s)} \mathrm{Im}F_{2A}^Z$$

$$\boxed{\begin{array}{cc} \mathcal{A}^{Re}_{\gamma,Z}\ \mathrm{L} & \mathcal{A}^{Re}_{\gamma,Z}\ \mathrm{L} \\ \mathcal{A}^{Im}_{\gamma,Z}\ \mathrm{R} & \mathcal{A}^{Im}_{\gamma,Z}\ \mathrm{R} \end{array}}$$

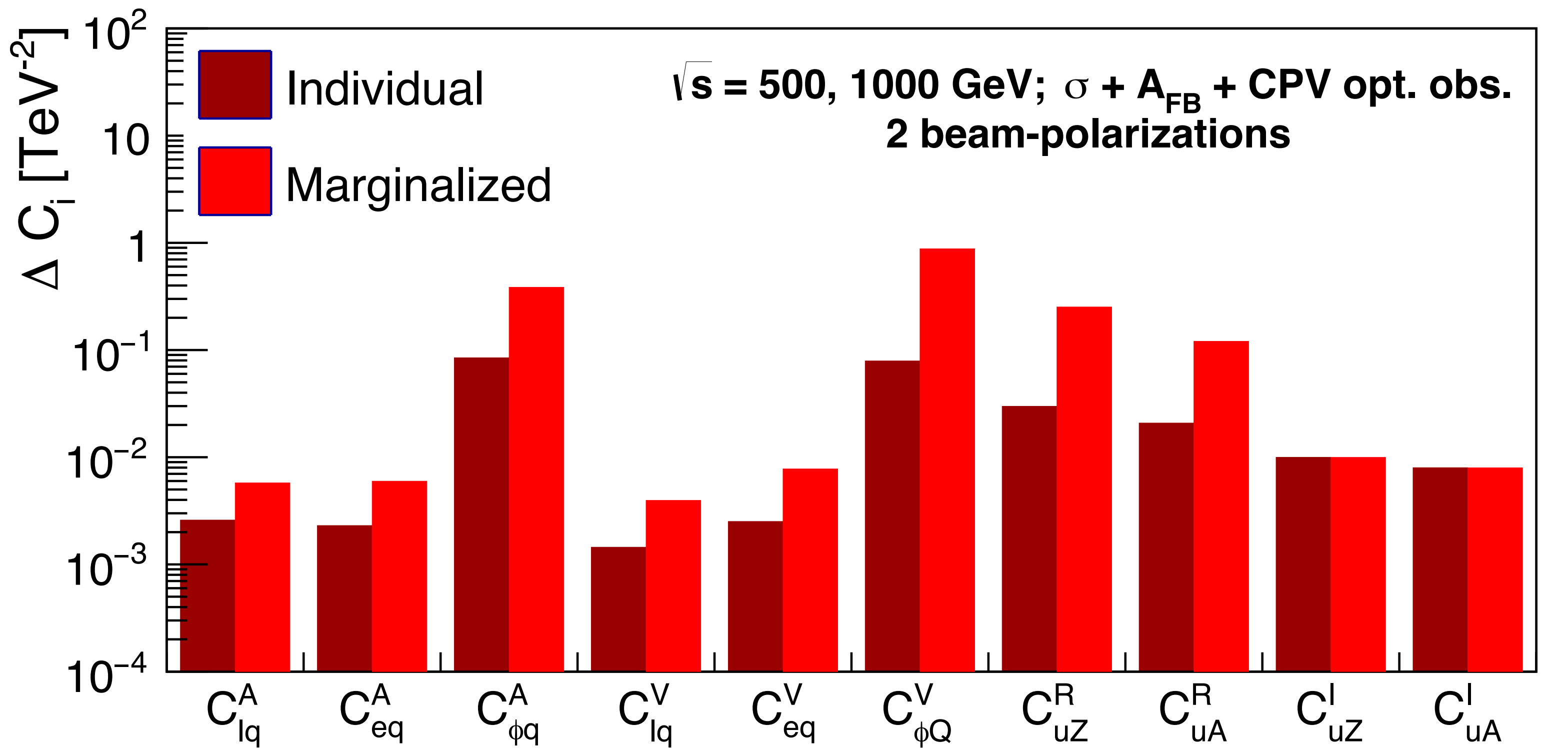
CPV observables in the global fit arXiv:1710.06737

Including CPV observables in the EFT global fit doesn't solve the problem

We still need to improve the marginalized fit



Theory fit, no full-simulation included.

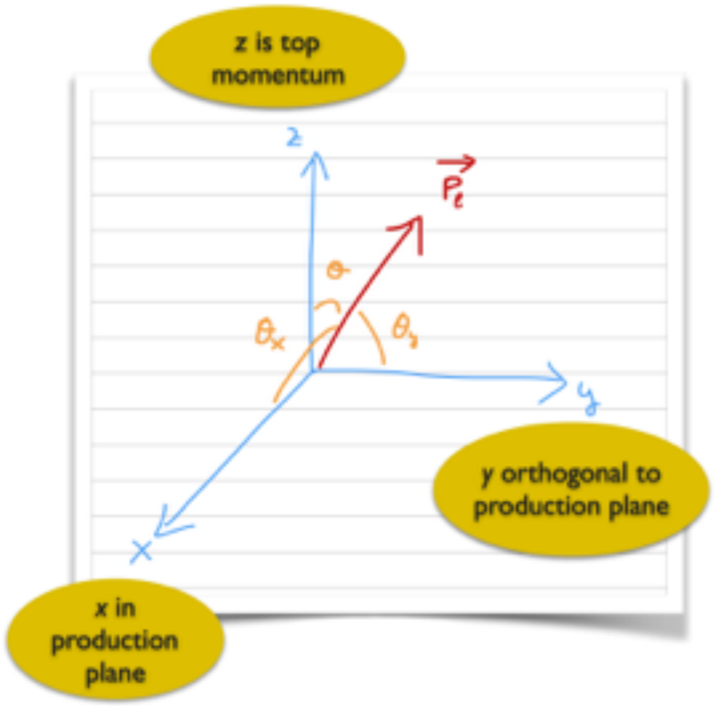


Individual: assuming variation in only 1 parameter each time.
Marginalized: assuming variation in all the parameters at the same time.

Further ideas using information from the decay: top quark polarization

Top quark polarization at different axes

J. A. Aguilar-Saavedra and J. Bernabeu. [arXiv:1005.5382].



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{1}{2}(1+\alpha P_3 \cos\theta)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_x} = \frac{1}{2}(1+\alpha P_1 \cos\theta_x)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_y} = \frac{1}{2}(1+\alpha P_2 \cos\theta_y)$$

Studied process

$$e^- e^+ \to t\bar{t} \to W^+ b W^- \bar{b} \to l\nu b\bar{b} q\bar{q}$$

Using the lepton from the leptonic W as a polarimeter, we can calculate the top polarization in 3 different axes.

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_i} = \frac{1}{2}(1+\alpha_i P \cos\theta_i)$$

Helicity axis (z): measuring top polarization in the z top momentum direction.

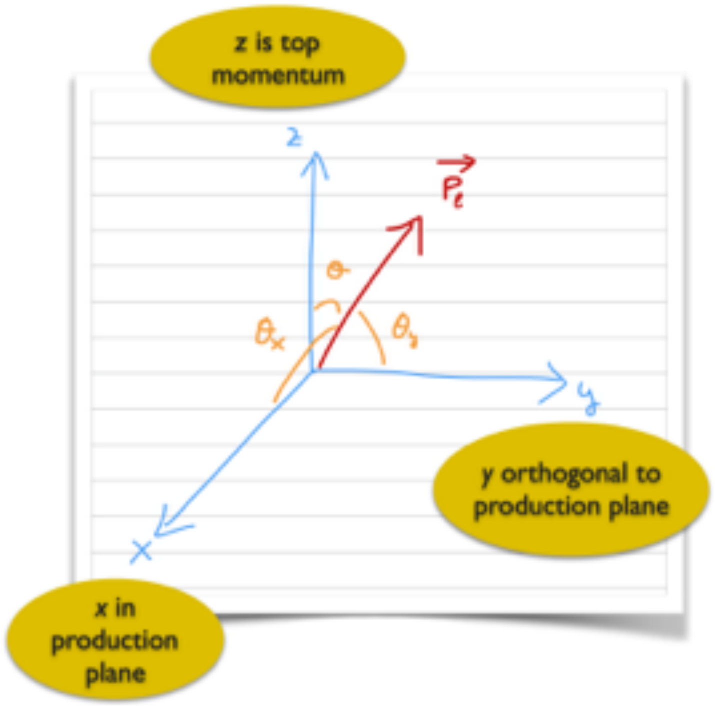
Overlapping with the forward-backward asymmetry.

arXiv:1505.06020v2

No new information.

Top quark polarization at different axes

J. A. Aguilar-Saavedra and J. Bernabeu. [arXiv:1005.5382].



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{1}{2}(1 + \alpha P_3 \cos\theta)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_x} = \frac{1}{2}(1 + \alpha P_1 \cos\theta_x)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_y} = \frac{1}{2}(1 + \alpha P_2 \cos\theta_y)$$

Studied process

$$e^-e^+ \to t\bar{t} \to W^+bW^-\bar{b} \to l\nu b\bar{b}q\bar{q}$$

Using the lepton from the leptonic W as a polarimeter, we can calculate the top polarization in 3 different axes.

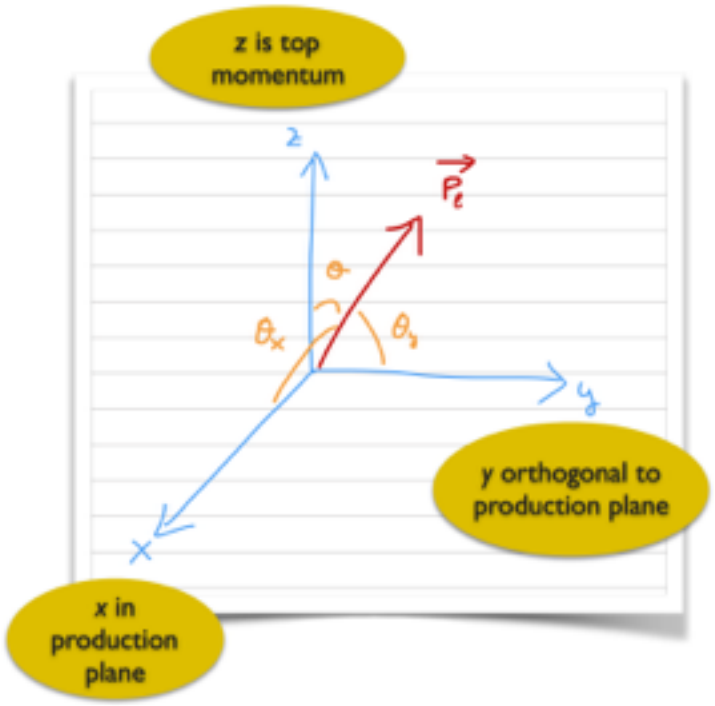
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_i} = \frac{1}{2}(1 + \alpha_i P \cos\theta_i)$$

Normal axis (x): measuring top polarization in the x direction, perpendicular to the production plane.

Same definition that the CPV observable ORe (see CPV slide). Insensitive to CP conserving operators.

Top quark polarization at different axes

J. A. Aguilar-Saavedra and J. Bernabeu. [arXiv:1005.5382].



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{1}{2}(1+\alpha P_3\cos\theta)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_x} = \frac{1}{2}(1+\alpha P_1\cos\theta_x)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_y} = \frac{1}{2}(1+\alpha P_2\cos\theta_y)$$

Studied process

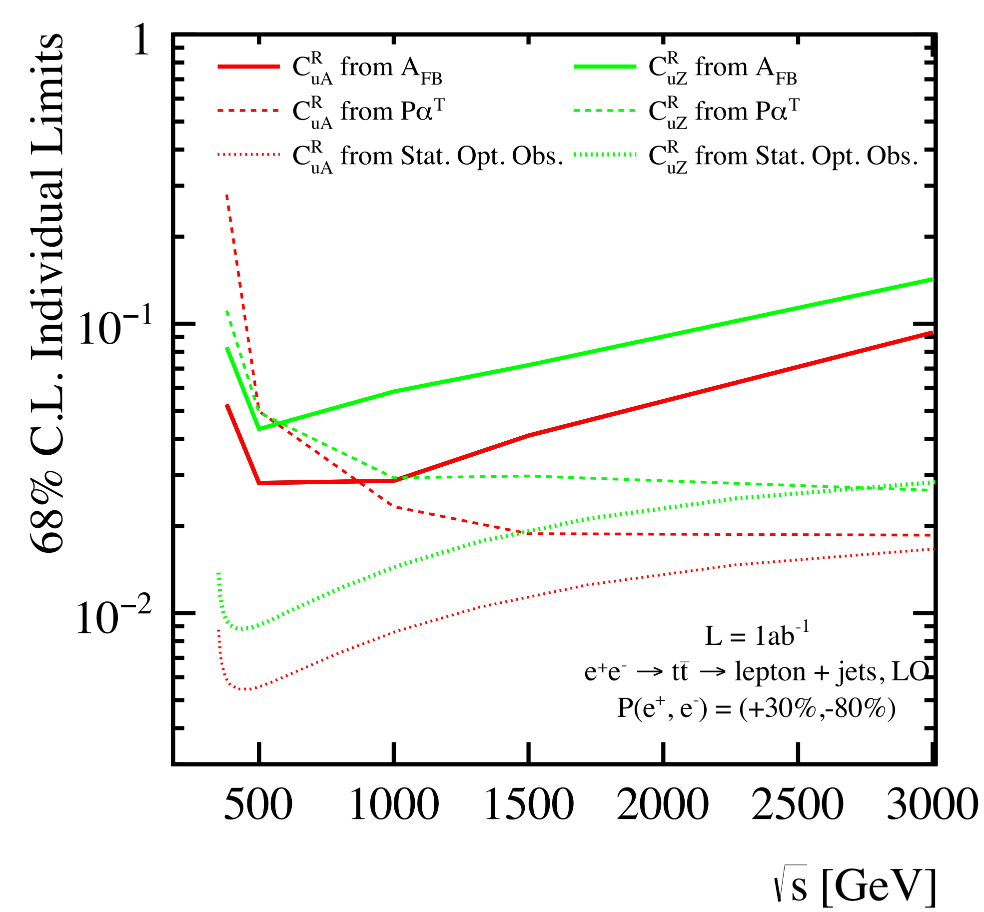
$$e^-e^+ \to t\bar{t} \to W^+bW^-\bar{b} \to l\nu b\bar{b}q\bar{q}$$

Using the lepton from the leptonic W as a polarimeter, we can calculate the top polarization in 3 different axes.

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_i} = \frac{1}{2}(1+\alpha_i P\cos\theta_i)$$

Transverse axis (y): measuring top polarization in the y direction, perpendicular to the x-z plane.

Seems to be good for constraining the real part of the dipole operators (CuA and CuZ)



Wtb vertex and W polarization

Wtb vertex

$$O_{uW} \equiv y_t g_W \;\; \bar{q}\tau^I \sigma^{\mu\nu} u \;\; \epsilon\varphi^* W^I_{\mu\nu}$$

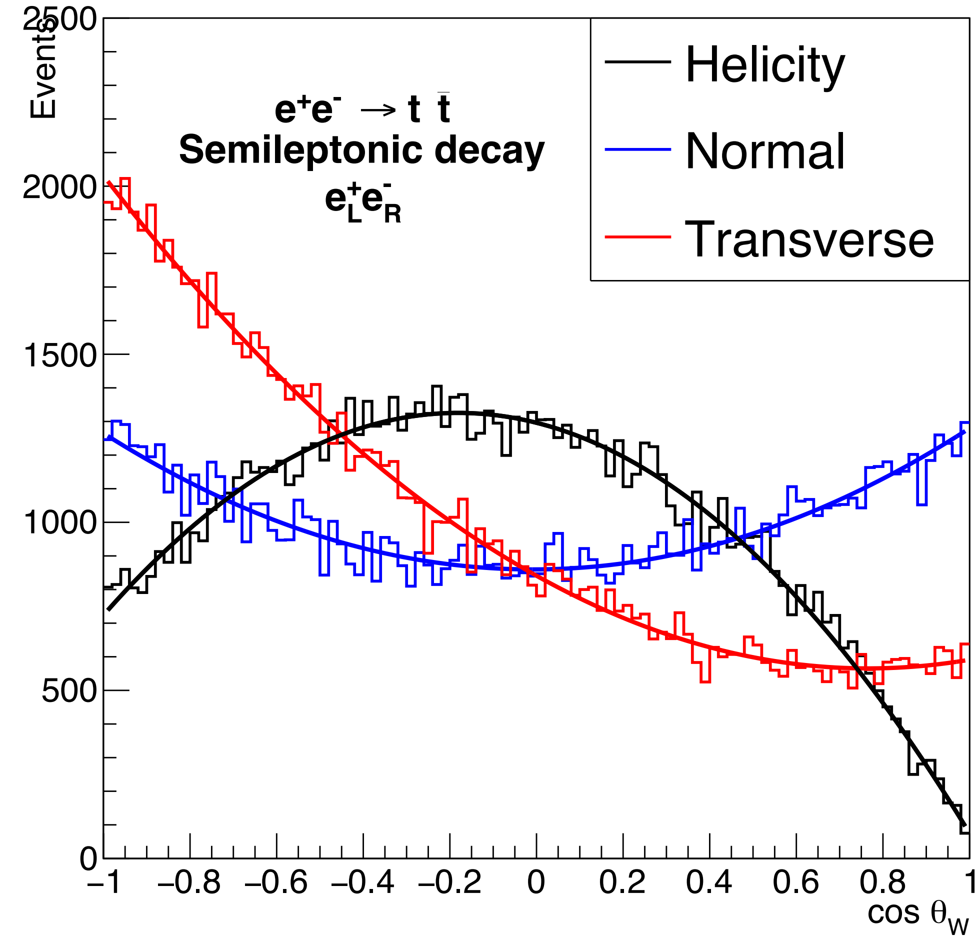
$$O^3_{\varphi q} \equiv \frac{y_t^2}{2} \;\; \bar{q}\tau^I \gamma^\mu q \;\; \varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi$$

$$O_{\varphi ud} \equiv \frac{y_t^2}{2} \;\; \bar{u}\gamma^\mu d \;\; \varphi^T \epsilon \, i D_\mu \varphi$$

$$O_{dW} \equiv y_t g_W \;\; \bar{q}\tau^I \sigma^{\mu\nu} d \;\; \epsilon\varphi^* W^I_{\mu\nu}$$

4 operators affecting to the top quark decay, 2 of them appear at production too.

Using the lepton from the leptonic W as a polarimeter, we can calculate the W polarization in 3 different axes (*same motivation than top polarization*).



J. A. Aguilar-Saavedra and J. Bernabeu. [arXiv:1005.5382].

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_l^*} = \frac{3}{8}F_+\left(1+\cos\theta_l^*\right)^2 + \frac{3}{4}F_0\sin^2\theta_l^* + \frac{3}{8}F_-\left(1-\cos\theta_l^*\right)^2$$

Wtb vertex

$$O_{uW} \equiv y_t g_W \;\; \bar{q}\tau^I\sigma^{\mu\nu}u \;\; \epsilon\varphi^* W^I_{\mu\nu}$$

$$O^3_{\varphi q} \equiv \frac{y_t^2}{2} \;\; \bar{q}\tau^I\gamma^\mu q \;\; \varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi$$

$$O_{\varphi ud} \equiv \frac{y_t^2}{2} \;\; \bar{u}\gamma^\mu d \;\; \varphi^T\epsilon\, iD_\mu\varphi$$

$$O_{dW} \equiv y_t g_W \;\; \bar{q}\tau^I\sigma^{\mu\nu}d \;\; \epsilon\varphi^* W^I_{\mu\nu}$$

4 operators affecting to the top quark decay, 2 of them appear at production too.

Defining: $A^W_{FB} \equiv \frac{3}{4}(F_+ - F_-)$

AT is proportional to the top quark transverse polarization

- $O_{\phi ud}$ and OdW only contribute quadratically (no SM interference).
- For these observables the dependence on $O_{\phi q3}$ also completely drops out.

Sensitivity to the real part of OuW at 500 GeV ***(Durieux, MP, Vos, Chang PRELIMINARY)***

$P(e^+, e^-)$	$(+30\%, -80\%)$		$(-30\%, +80\%)$	
observables	A^T	A^W_{FB}	A^T	A^W_{FB}
SM predictions	-0.6	-0.17	0.57	-0.29
in production	38 ± 1	9 ± 2	-25 ± 1	X
in decay	X	16 ± 2	X	11 ± 3
in prod. & decay	37 ± 1	26 ± 2	-24 ± 1	10 ± 3

Statistically optimal observables

G. Durieux @TopLC 2017:

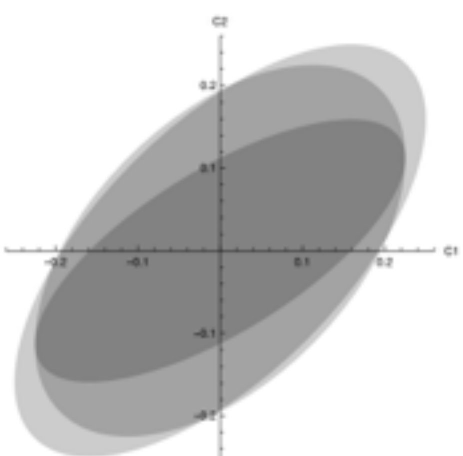
https://indico.cern.ch/event/595651/contributions/

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

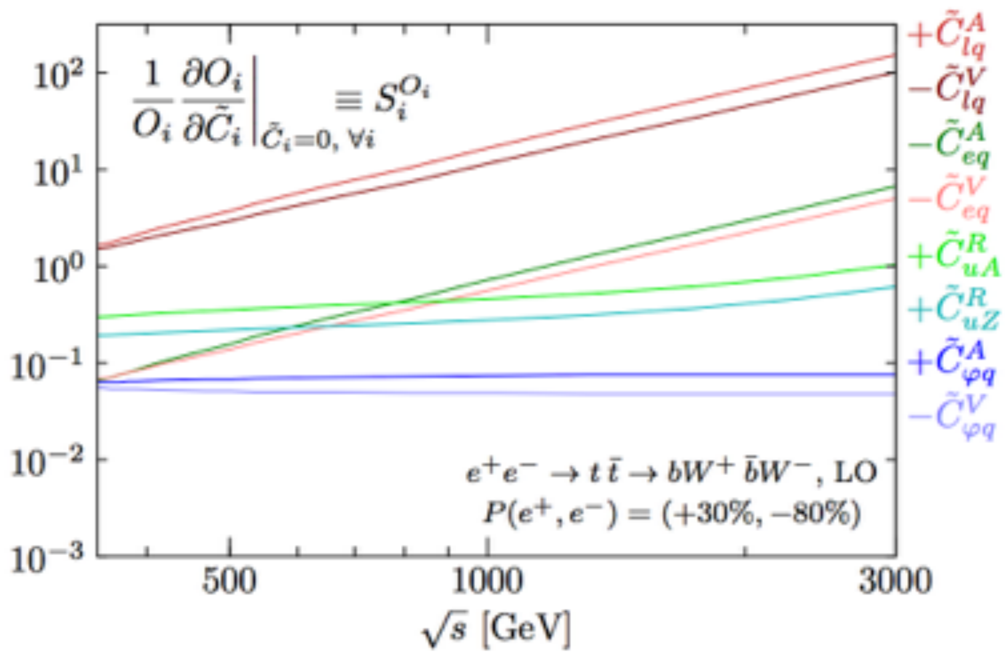
$\Longrightarrow$ area ratios 1.9 : 1.7 : 1

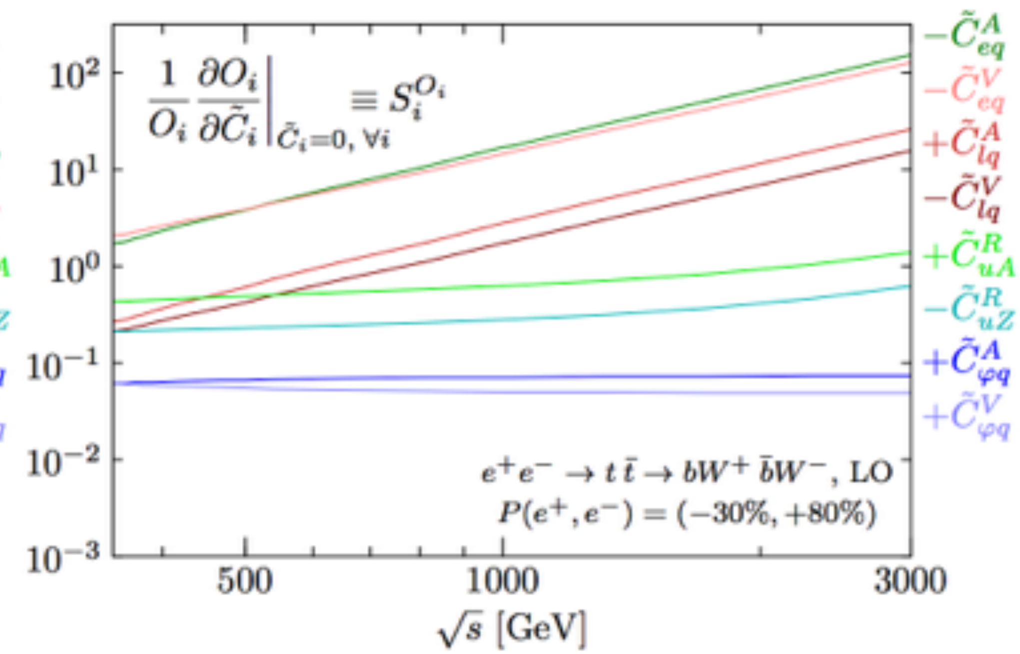
Previous applications in $e^+e^- \to t\bar{t}$:
[Grzadkowski, Hioki '00] [Janot '15] [Khiem et al '15]

Construction based on the decomposition of the differential $e^+e^- \to t\bar{t} \to bW^+\bar{b}W^-$ 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.

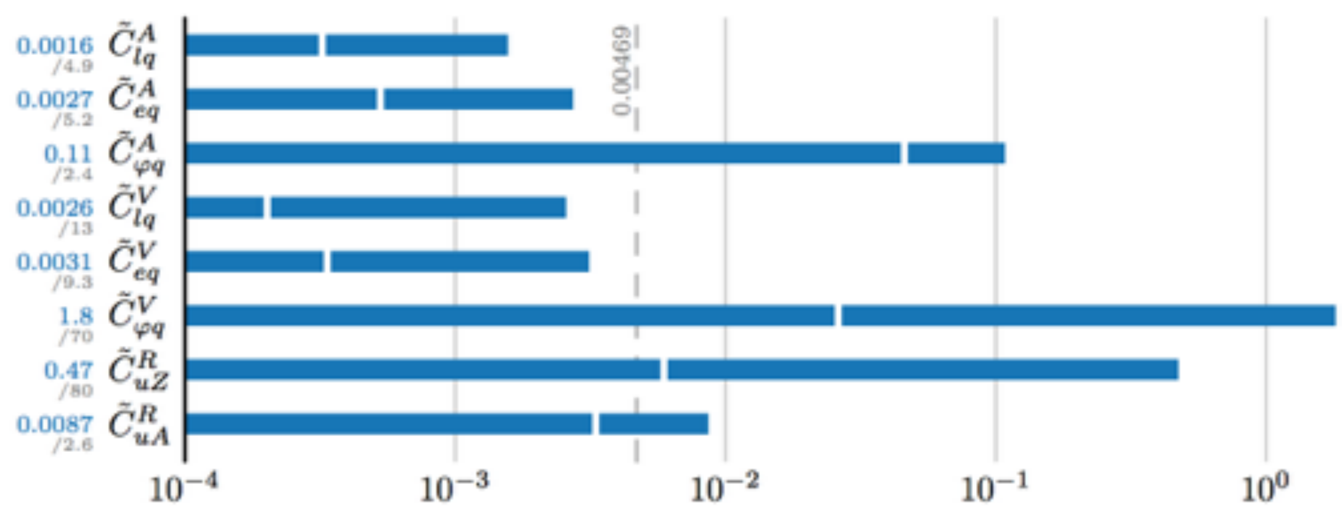
Statistically optimal observables sensitivities



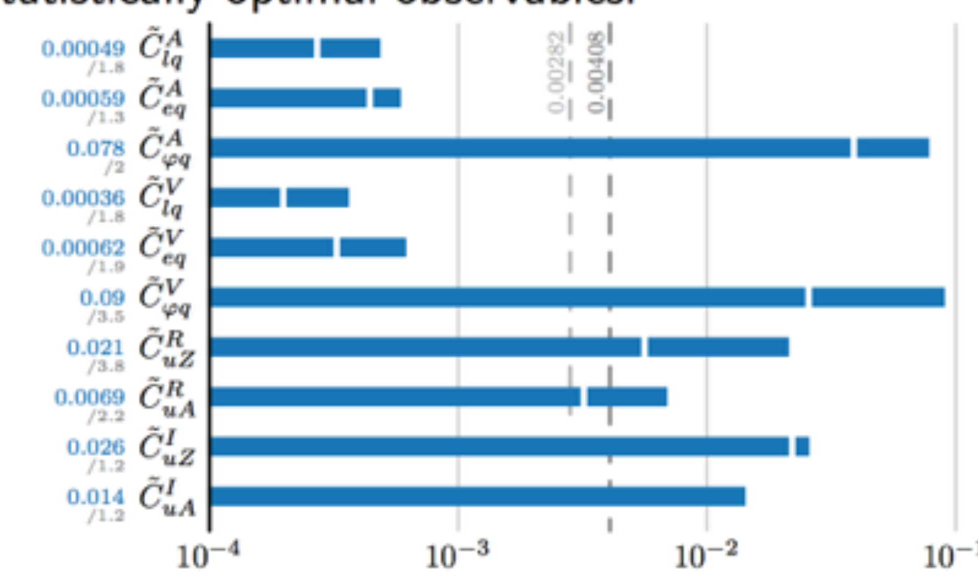


Comparison in the global limits (500GeV + 1TeV for 2 pols.):

$\sigma + A_{FB}$



Statistically optimal observables:



- **Even better individual limits**
- **Global limits within a factor 1.3 to 3.5**

(Few words about) Full-simulation

See "*Top identification and ttbar reconstruction at CLIC*" from R. Ström on Wednesday morning for more details

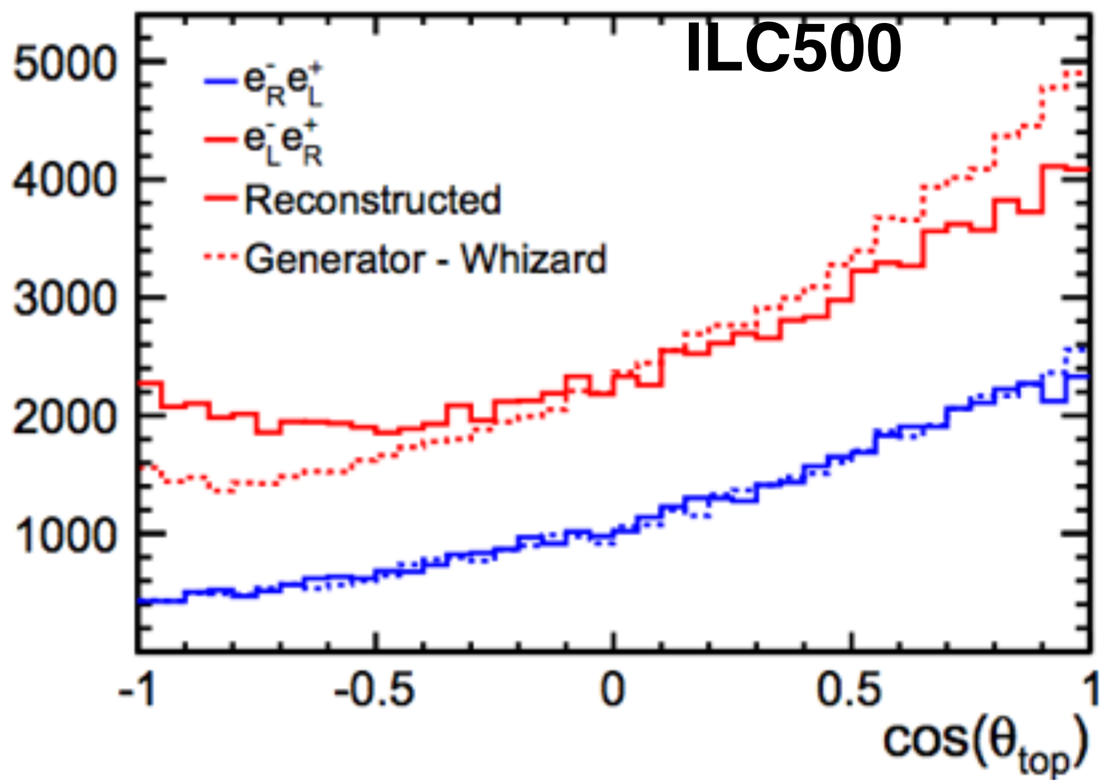
Full-simulation

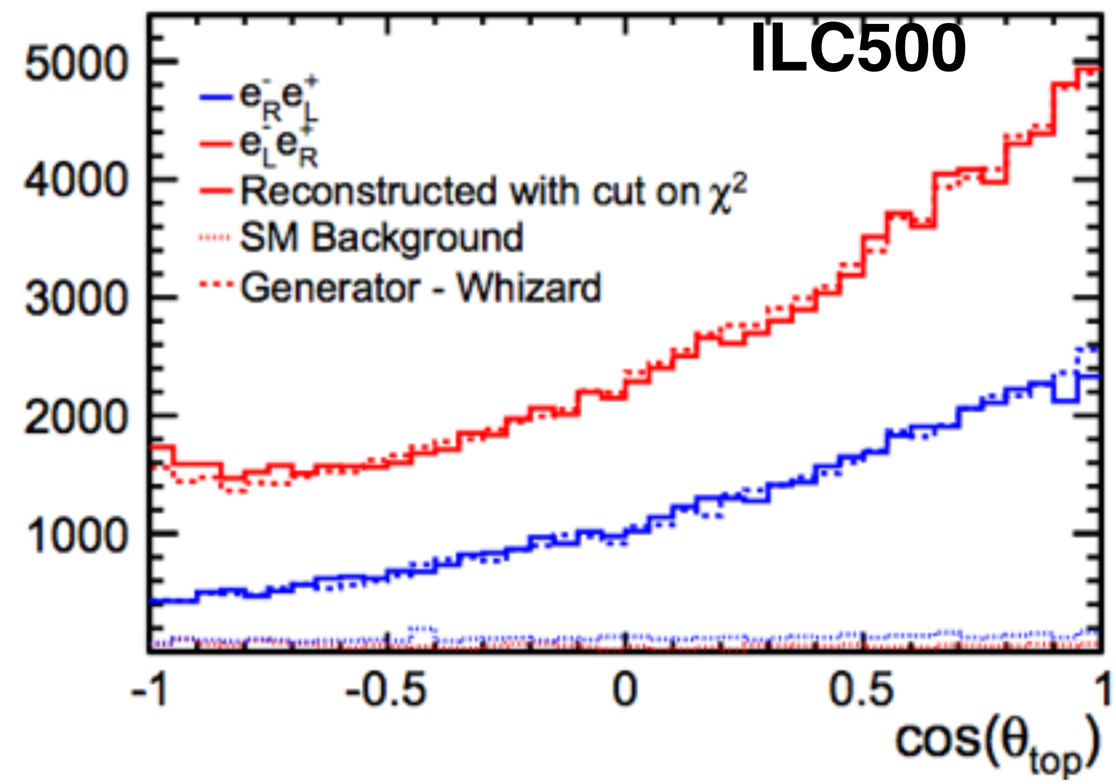
Reconstructed process: e-e+ —> tt—> 4j + vl

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.





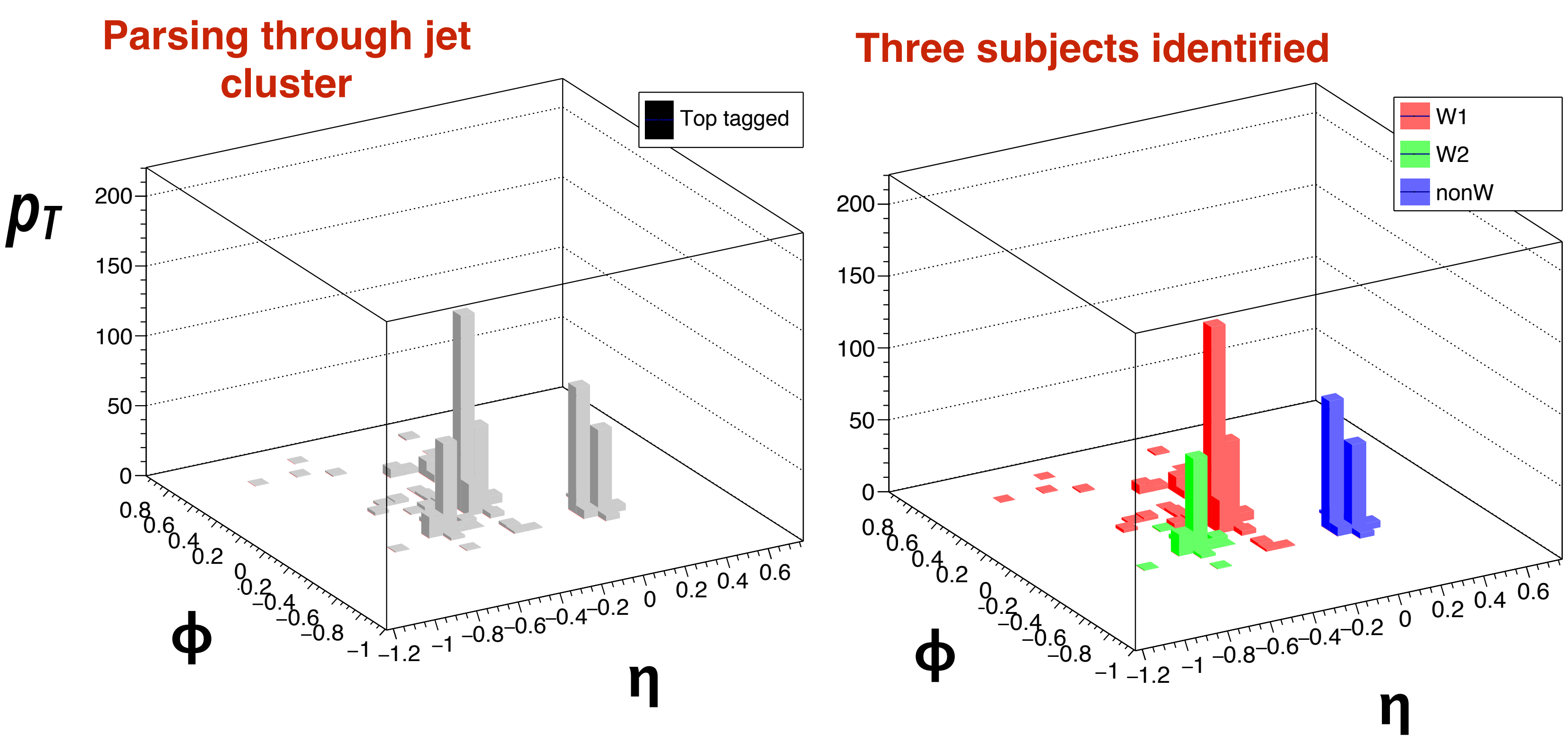
Alternative: reconstruction of b quark charge (see R. Poeschl talk on Tuesday afternoon)

Full-simulation

Reconstructed process: e-e+ —> tt—> 4j + vl

CLIC1400 and CLIC3000

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



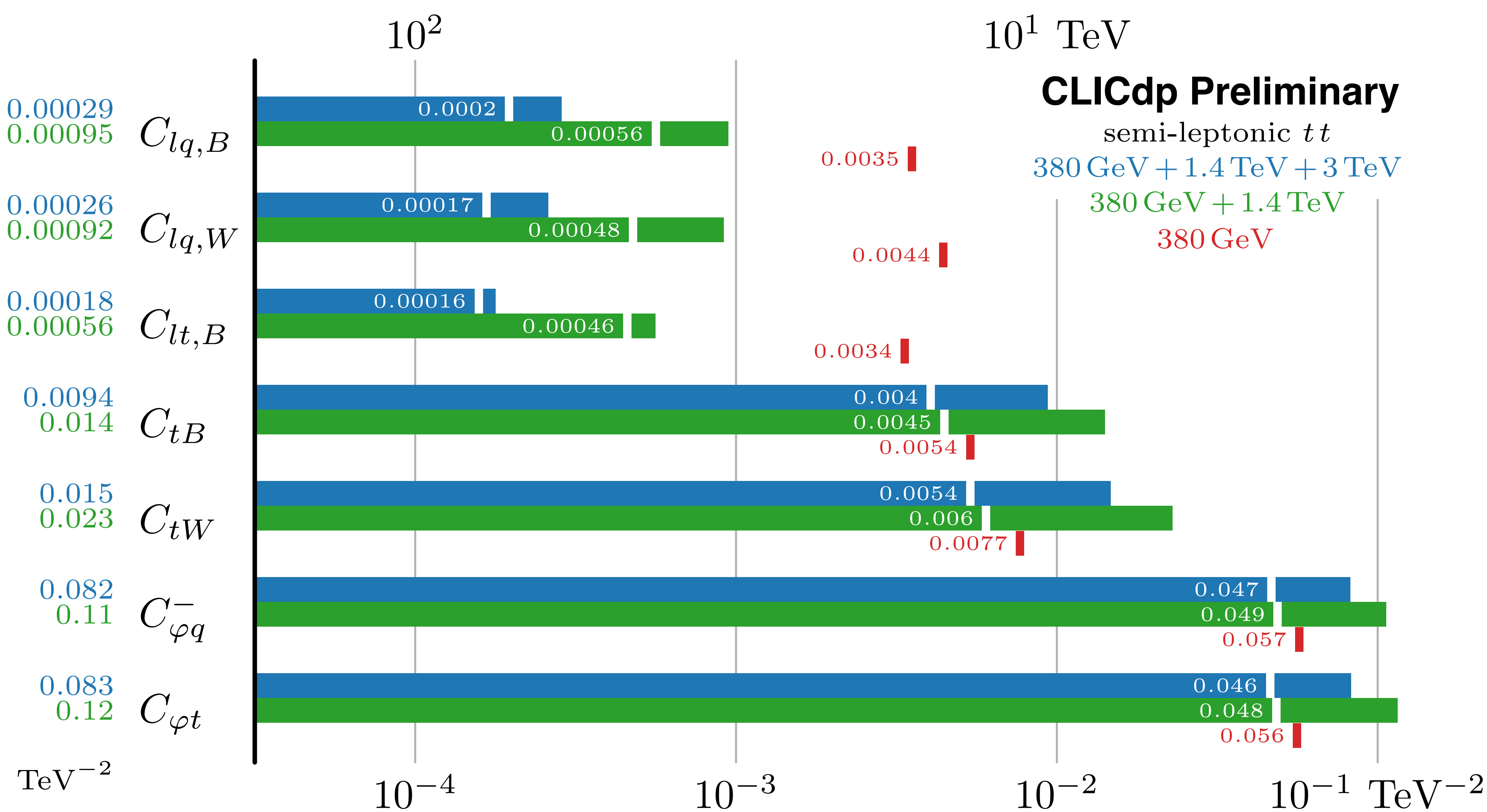
See R. Ström talk to understand all the work behind this method

Results based on CLIC

Results based on CLIC

Top-philic basis (arXiv:1802.07237)

A top-philic scenario is obtained by assuming that new physics couples dominantly to the left-handed doublet and right- handed up-type quark singlet of the third generation as well as to bosons.



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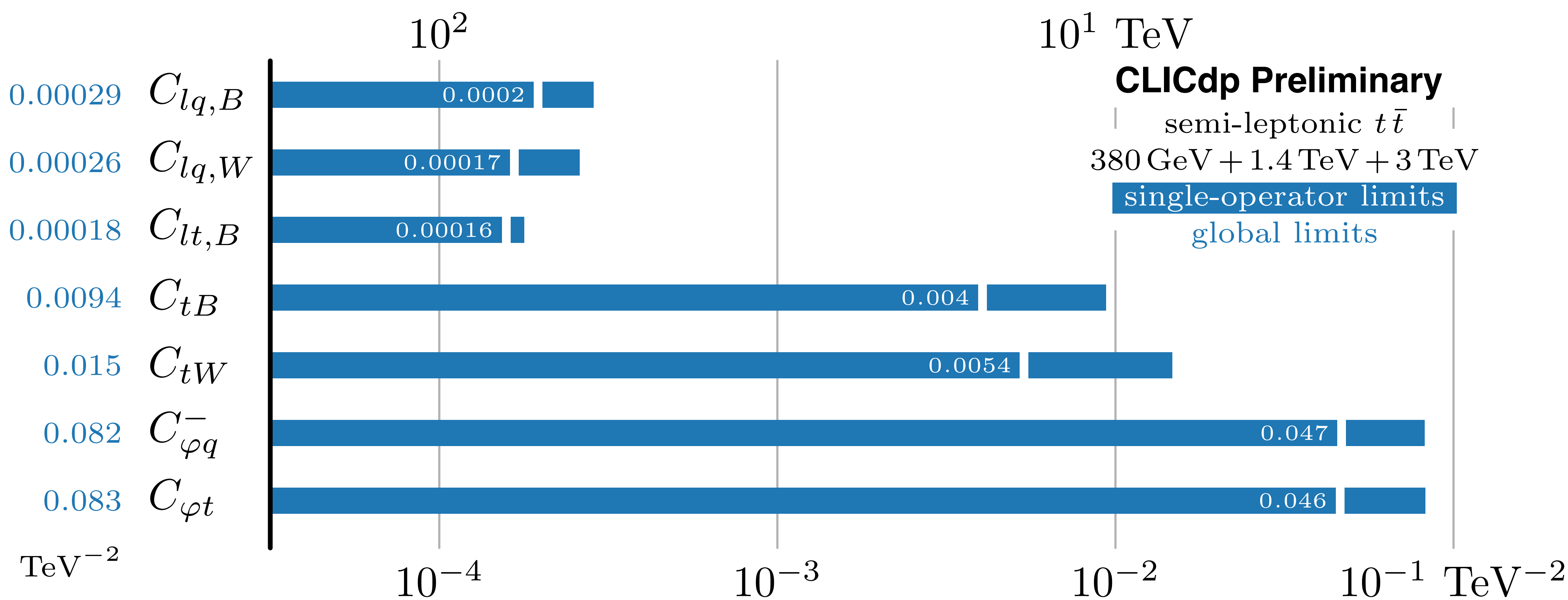

Difference between individual and marginalised limit lower than a factor 2 for 4-fermion operators and lower than a factor 4 for 2-fermion

Results based on CLIC

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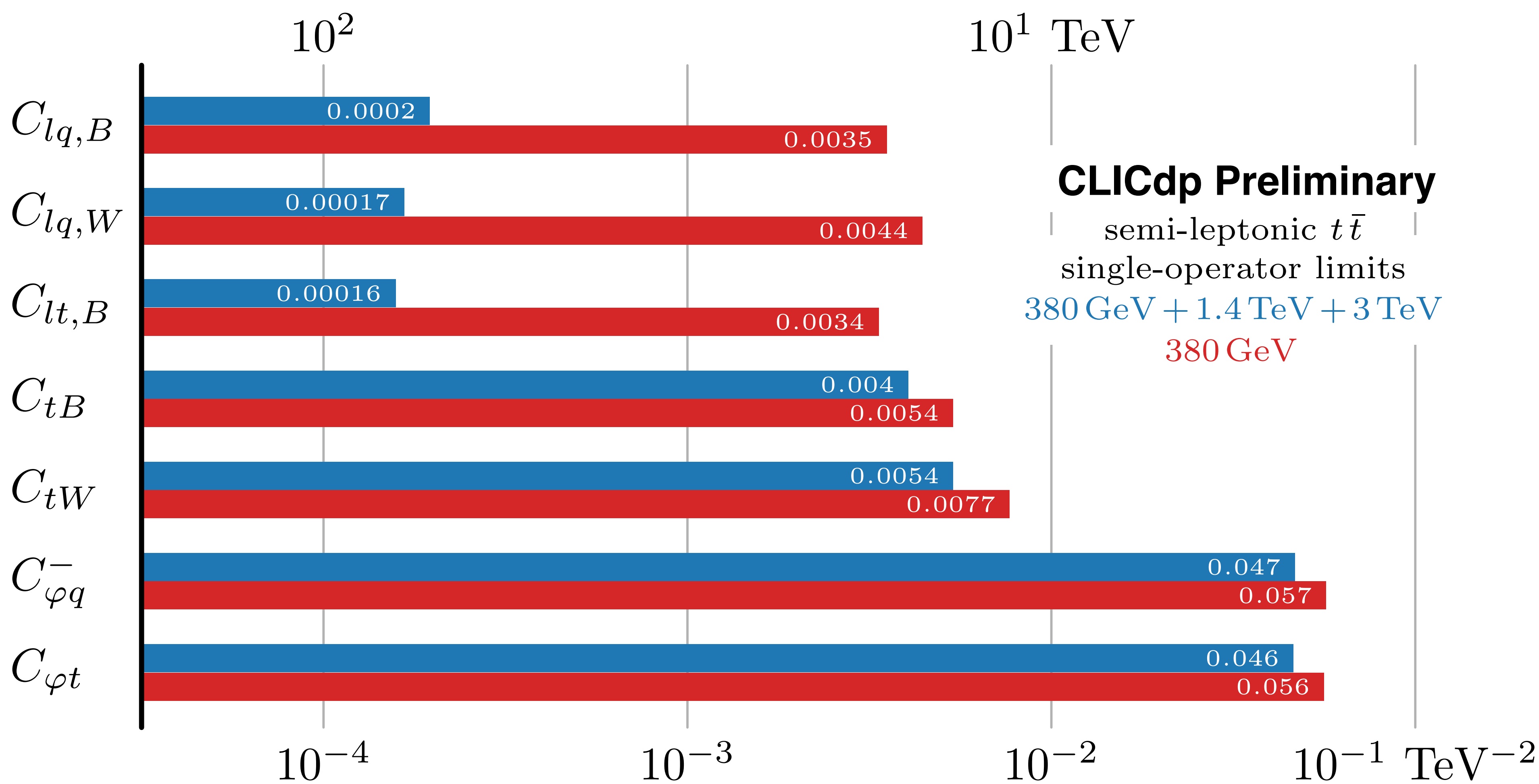
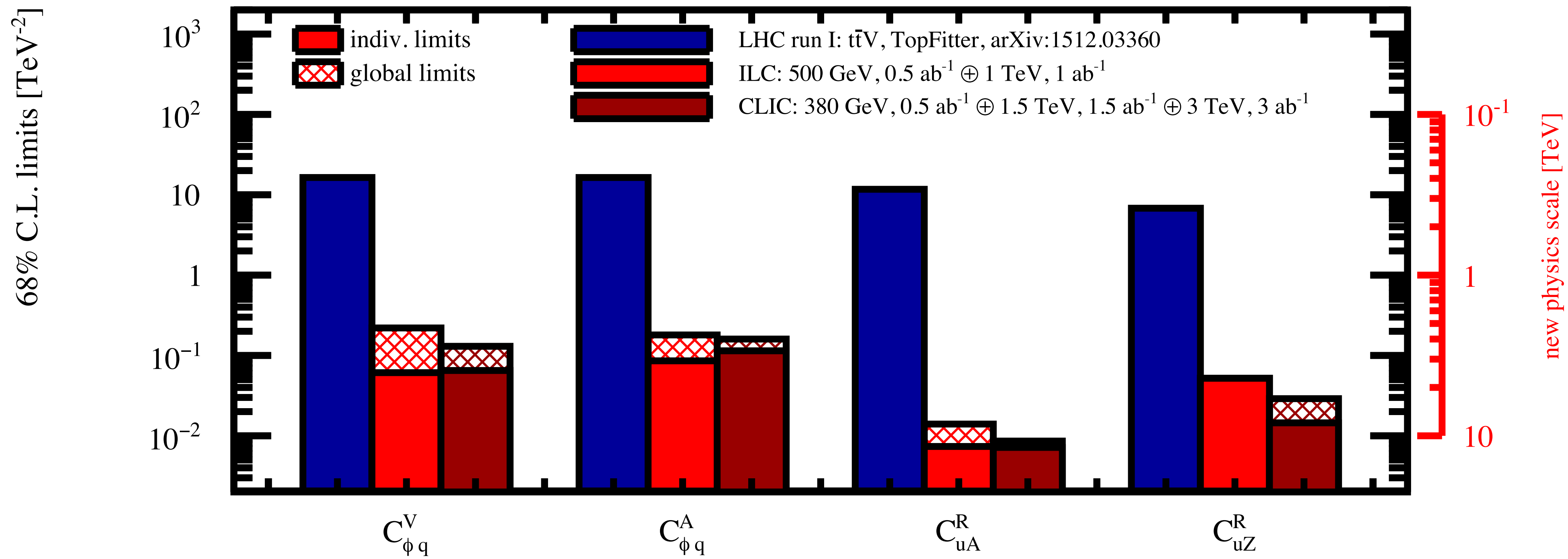


CLIC at high energy has a great potential to constrain 4-fermion operators

Comparison with the LHC

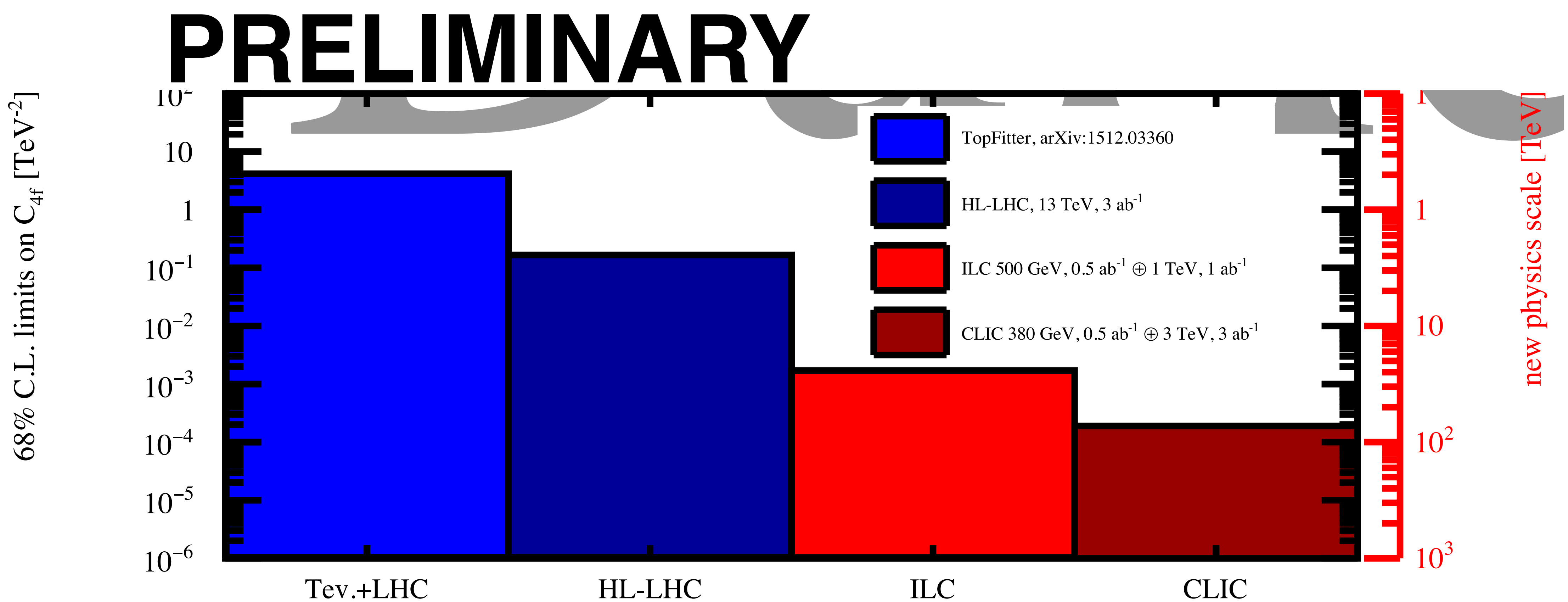
Comparison with the LHC: vertices

PRELIMINARY



- Still **preliminary**, final results for ILC still coming.
- Limits between 2 and 3 orders of magnitude better than LHC.
- LHC limits could improve in future stages, but not prospects of this possible improvement at the moment.

Comparison with the LHC: contact interactions



- Still **preliminary**, final results for ILC still coming.
- Top-philic scenario allows for a comparison between qqtt and eett contact interaction.
- LHC results could be improved using boosted measurements on (MP, Vos, arXiv:1512.07542), but even so couldn't surpass LC limits (3 - 4 orders of magnitude better at the moment).

Summary on the global fit

- Cross-section + A_{FB} alone are not optimal for a global EFT fit.
- CP-odd operators well constrained by CP-odd optimal observables.
- Only one energy point is not enough for constrain the full set of operators.
- Optimal observables seem to be the proper solution to the global fit.
- Results on the global fit ready for the CLICdp top quark paper (preparing pheno paper including ILC scenario).

Back up

CPV: Optimal CP-odd observables

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**.

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

$$\begin{aligned} t\ \bar{t} \quad &\rightarrow \quad \ell^+(\mathbf{q}_+) + \nu_\ell + b + \overline{X}_{\rm had}(\mathbf{q}_{\bar{X}}) \\ t\ \bar{t} \quad &\rightarrow \quad X_{\rm had}(\mathbf{q}_X) + \ell^-(\mathbf{q}_-) + \bar{\nu}_\ell + \bar{b} \end{aligned}$$

- **CP-odd observables** are defined with the **four momenta available in tt semi-leptonic decay channel**

$$\begin{aligned} \mathcal{O}_+^{Re} &= (\hat{\mathbf{q}}_{\bar{X}} \times \hat{\mathbf{q}}_+^*) \cdot \hat{\mathbf{p}}_+ \,, \\ \mathcal{O}_+^{Im} &= -[1 + (\frac{\sqrt{s}}{2m_t} - 1)(\hat{\mathbf{q}}_{\bar{X}} \cdot \hat{\mathbf{p}}_+)^2]\hat{\mathbf{q}}_+^* \cdot \hat{\mathbf{q}}_{\bar{X}} + \frac{\sqrt{s}}{2m_t}\hat{\mathbf{q}}_{\bar{X}} \cdot \hat{\mathbf{p}}_+ \hat{\mathbf{q}}_+^* \cdot \hat{\mathbf{p}}_+ \end{aligned}$$

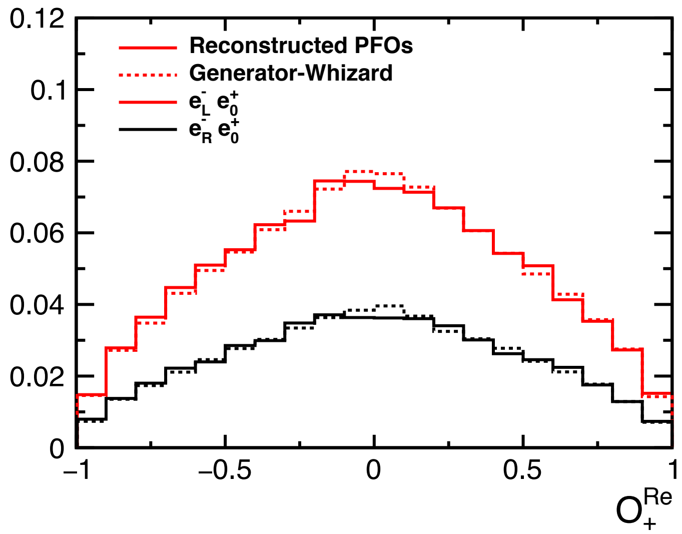
- The way to **extract** the **CP-violating form factor** is to construct **asymmetries sensitive to CP-violation effects**

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

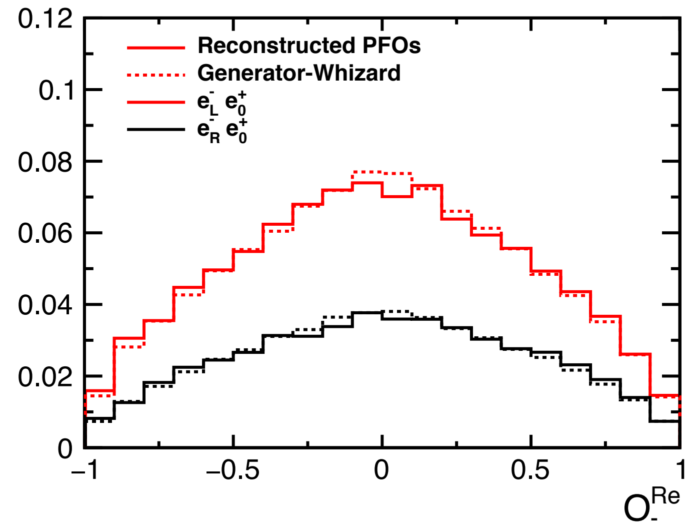
$$\mathcal{A}^{Im} = \langle \mathcal{O}_+^{Im} \rangle - \langle \mathcal{O}_-^{Im} \rangle = \boxed{\tilde{c}_\gamma(s)} {\rm Im} F_{2A}^\gamma + \boxed{\tilde{c}_Z(s)} {\rm Im} F_{2A}^Z$$

$$\boxed{\begin{array}{cc} \mathcal{A}_{\gamma,Z}^{Re\ \mathrm{L}} & \mathcal{A}_{\gamma,Z}^{Re\ \mathrm{L}} \\ & \\ \mathcal{A}_{\gamma,Z}^{Im\ \mathrm{R}} & \mathcal{A}_{\gamma,Z}^{Im\ \mathrm{R}} \end{array}}$$

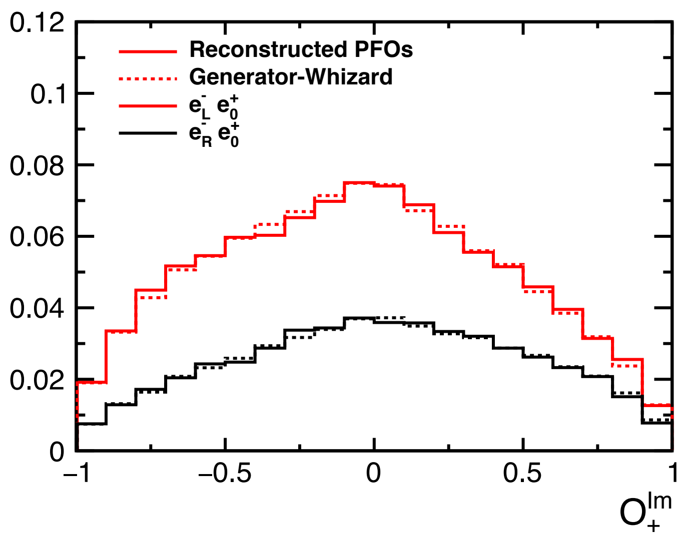
CPV: Full-simulation: CLIC@380GeV



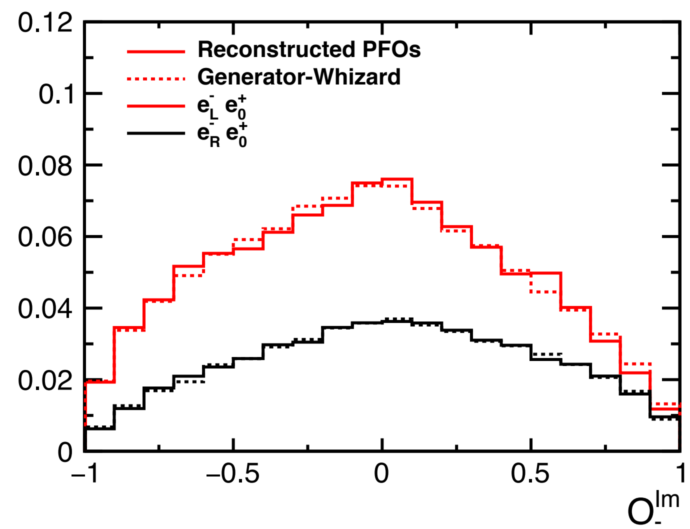
(a) $\mathcal{O}^{Re}_+$



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



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

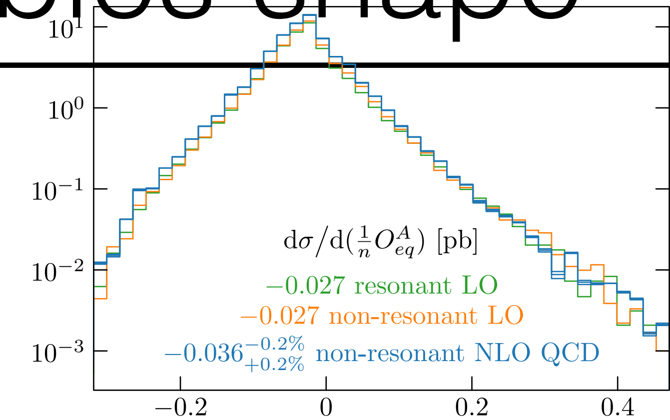


(d) $\mathcal{O}^{Im}_-$

polarization	e^-_L $(P_{e^-} = -0.8)$	e^-_R $(P_{e^-} = +0.8)$
$\mathcal{A}^{Re}$	-0.00006 $\pm$ 0.003	0.0072 $\pm$ 0.003
$\mathcal{A}^{Im}$	0.0004 $\pm$ 0.003	-0.0019 $\pm$ 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

Statistically optimal observables shape



Example for 500 GeV (e-, e+) = (-0.8, 0.3)

Theory uncertainties under study

Generated plots