EFT fit on top quark EW couplings

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Introduction

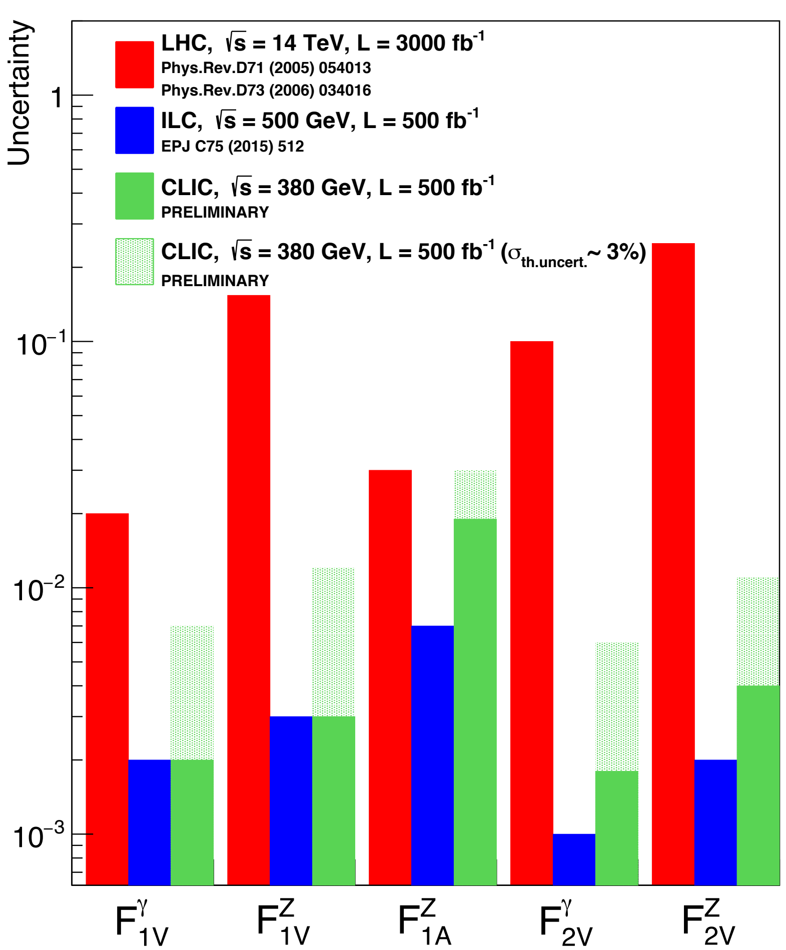
Top quark couplings: form factors

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

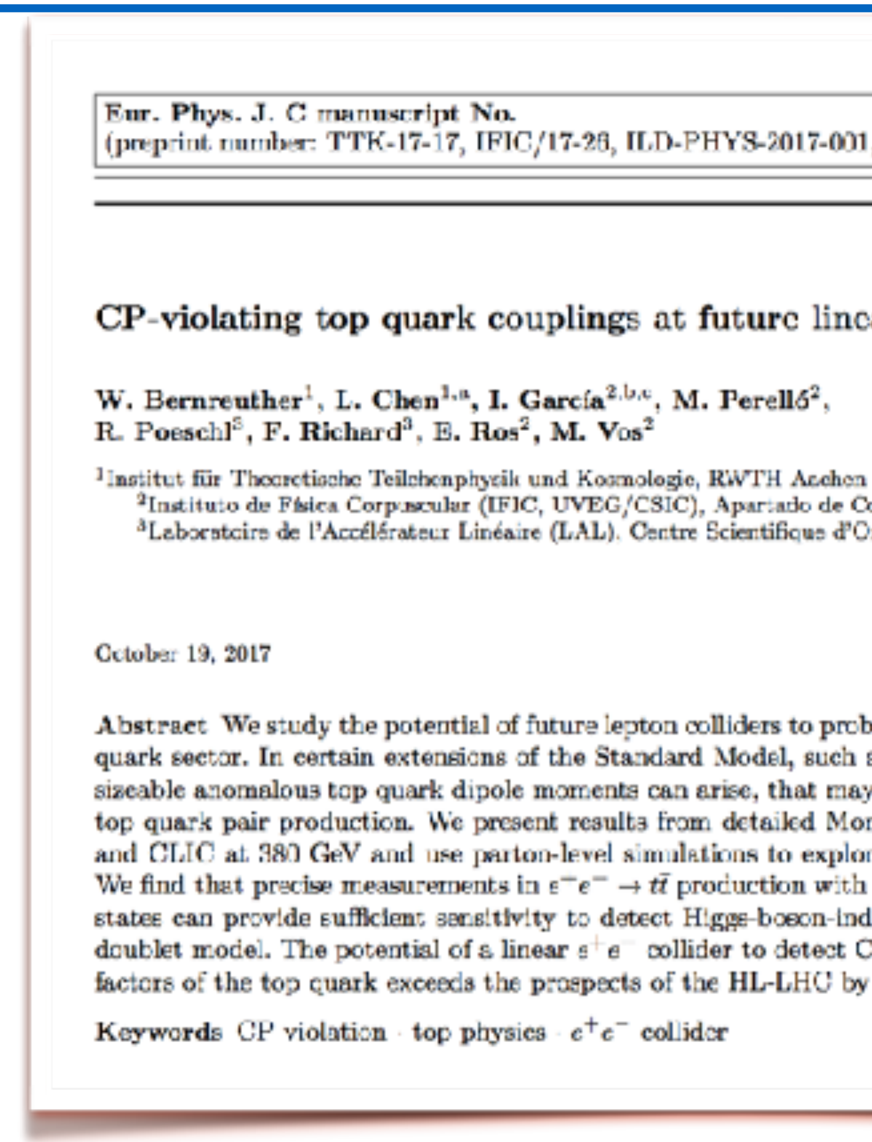
Form-factors
$$\Gamma_\mu^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(\underline{F_{1V}^X(k^2)} + \gamma_5 \underline{F_{1A}^X(k^2)}\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(i\underline{F_{2V}^X(k^2)} + \gamma_5 \underline{F_{2A}^X(k^2)}\right)\right\}$$

CP Conserving **CPV**

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



arXiv:1710.06737



Eur. Phys. J. C manuscript No.
(preprint number: TTK-17-17, IFIC/17-26, ILD-PHYS-2017-001, CLICdp-PUB-2017-003)

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

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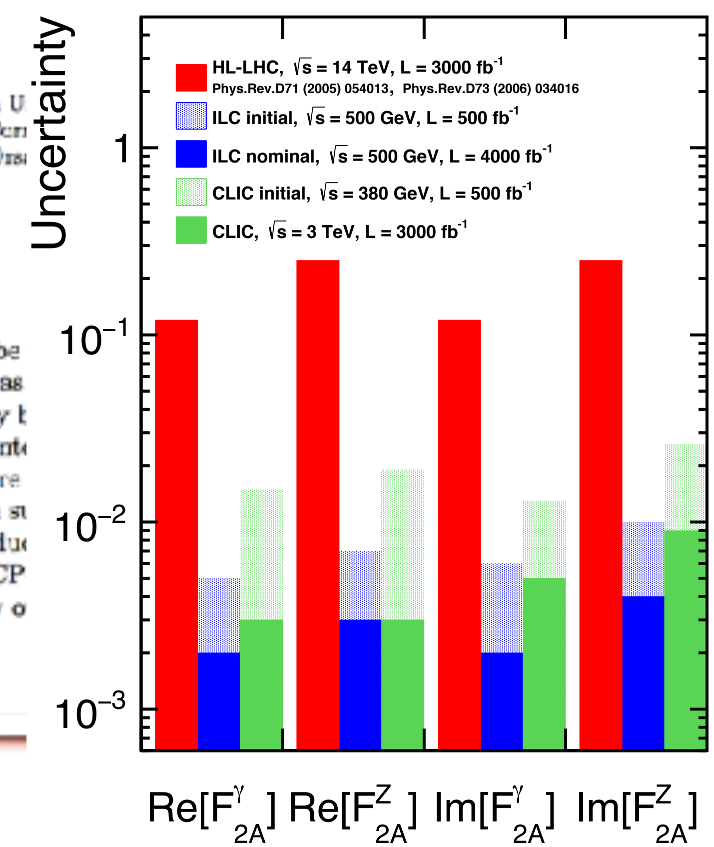
October 19, 2017

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 b... top quark pair production. We present results from detailed Monte... 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 su... states can provide sufficient sensitivity to detect Higgs-boson-induc... 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

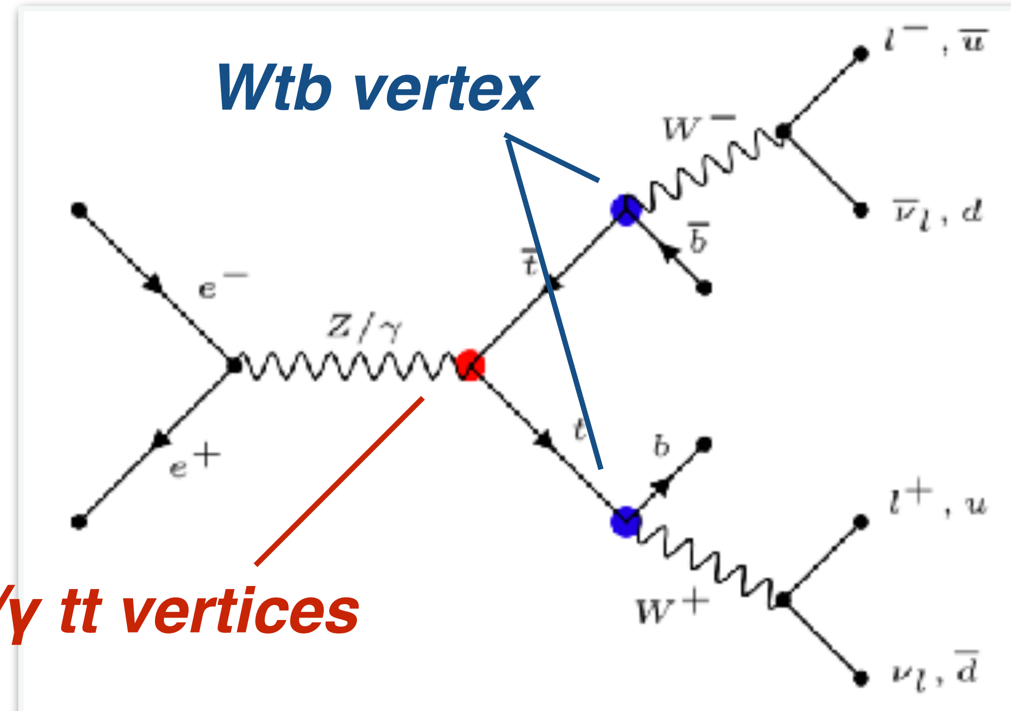
Effective Field Theory

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

dim-6 operators

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

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

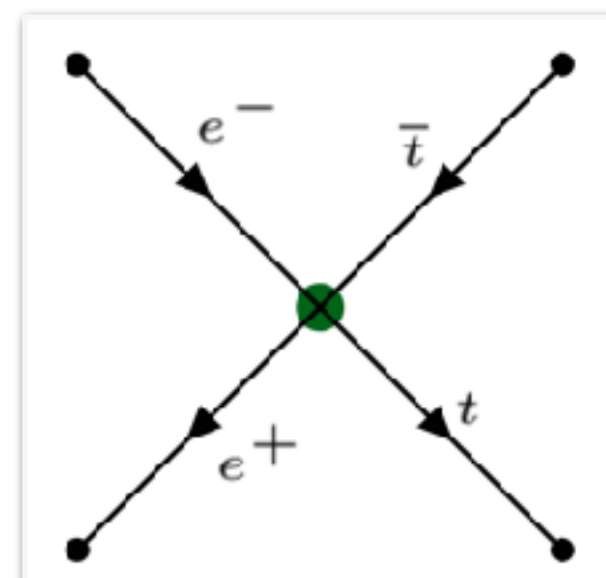


Contact interactions

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

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

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



Different EFT basis

Transformation between effective operators and form-factors:

$$
\begin{aligned}
F_{1,V}^{Z} - F_{1,V}^{Z,SM} &= \frac{1}{2}\left(C_{\varphi Q}^{(3)} - C_{\varphi Q}^{(1)} - C_{\varphi t}\right)\frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2} C_{\varphi q}^{V} \frac{m_t^2}{\Lambda^2 s_W c_W} \\
F_{1,A}^{Z} - F_{1,A}^{Z,SM} &= \frac{1}{2}\left(-C_{\varphi Q}^{(3)} + C_{\varphi Q}^{(1)} - C_{\varphi t}\right)\frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2} C_{\varphi q}^{A} \frac{m_t^2}{\Lambda^2 s_W c_W} \\
F_{2,V}^{Z} &= \left(\mathrm{Re}\{C_{tW}\} c_W^2 - \mathrm{Re}\{C_{tB}\} s_W^2\right)\frac{4m_t^2}{\Lambda^2 s_W c_W} = \mathrm{Re}\{C_{uZ}\}\frac{4m_t^2}{\Lambda^2} \\
F_{2,V}^{\gamma} &= \left(\mathrm{Re}\{C_{tW}\} + \mathrm{Re}\{C_{tB}\}\right)\frac{4m_t^2}{\Lambda^2} = \mathrm{Re}\{C_{uA}\}\frac{4m_t^2}{\Lambda^2} \\
\left[F_{2,A}^{Z}, F_{2,A}^{\gamma}\right] &\propto \left[\mathrm{Im}\{C_{tW}\}, \mathrm{Im}\{C_{tB}\}\right]
\end{aligned}
$$

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

Conversion to V/A - V basis in contact interactions:

$$
\begin{aligned}
C_{lq}^{V} &\equiv C_{lu} + C_{lq}^{(1)} - C_{lq}^{(3)} & \qquad C_{eq}^{V} &\equiv C_{eu} + C_{eq} \\
C_{lq}^{A} &\equiv C_{lu} - C_{lq}^{(1)} + C_{lq}^{(3)} & \qquad C_{eq}^{A} &\equiv C_{eu} - C_{eq}
\end{aligned}
$$

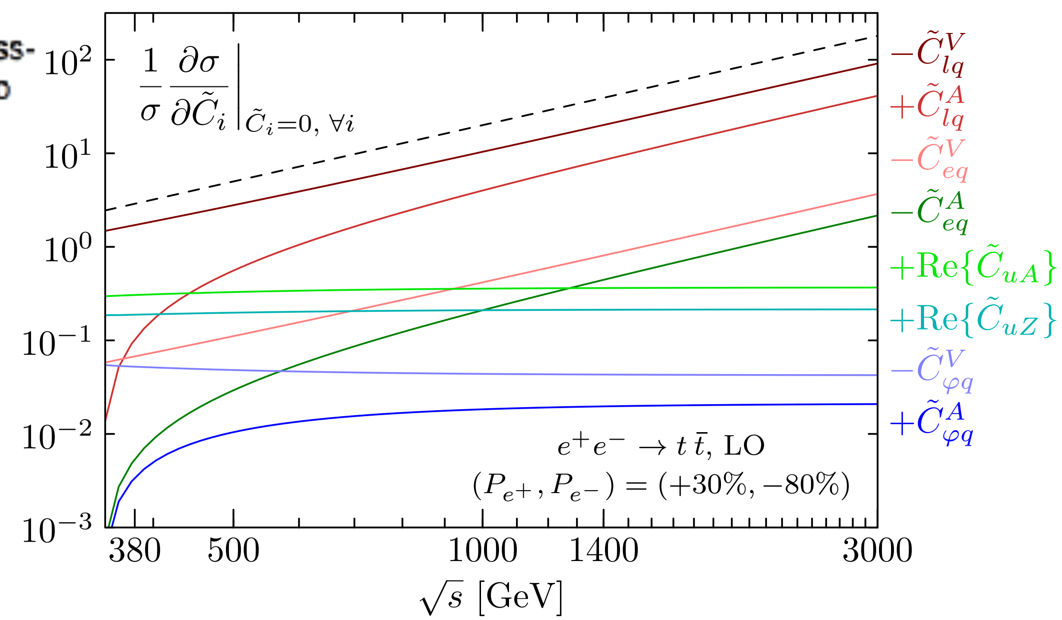
Observables

Observables sensitivity: A_{FB} + cross-section

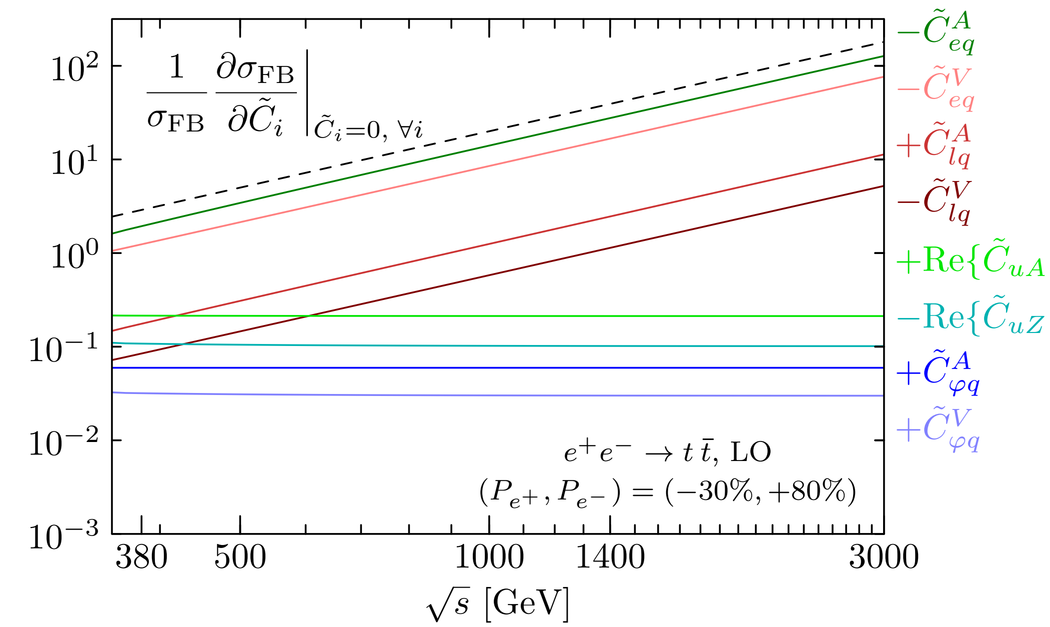
$e^+e^- \to t\,\bar{t}$, LO **Durieux, Perelló, Vos, Zhang, to be published**

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

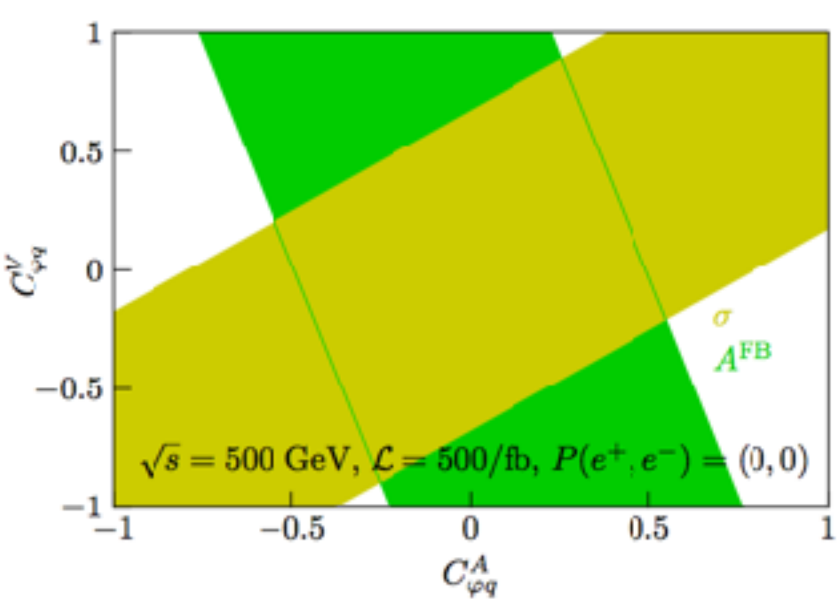
Cross-section

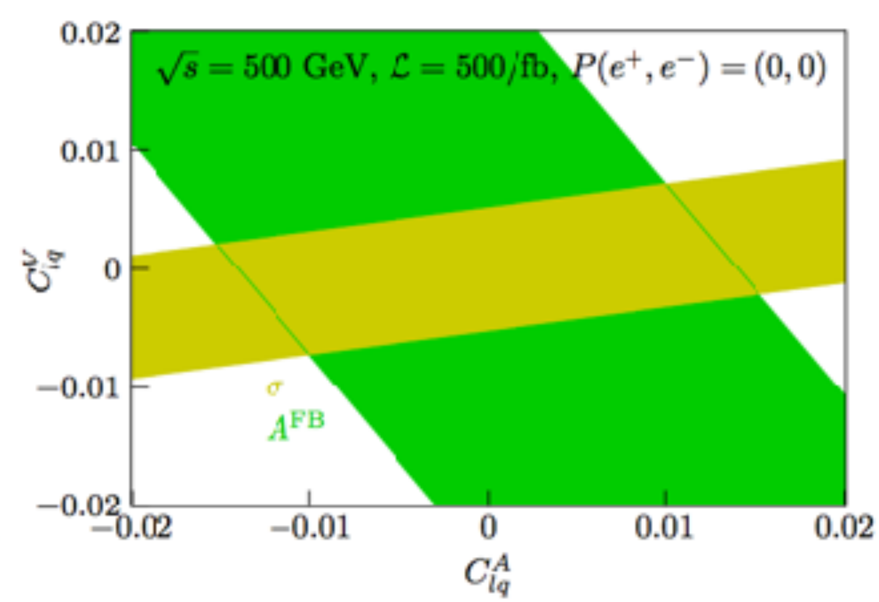


Forward-backward asymmetry



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





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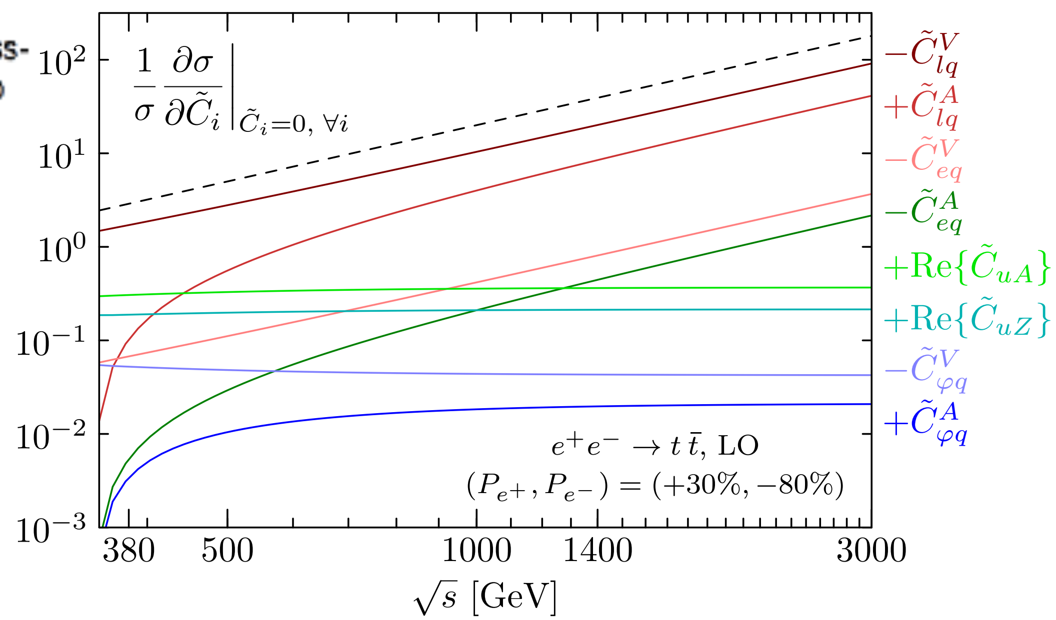
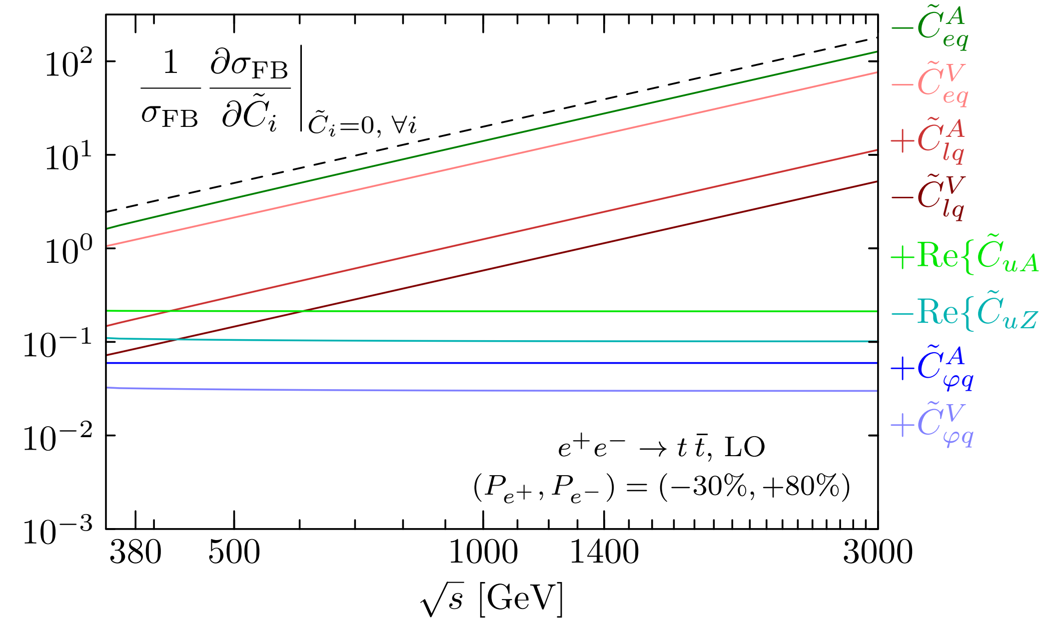
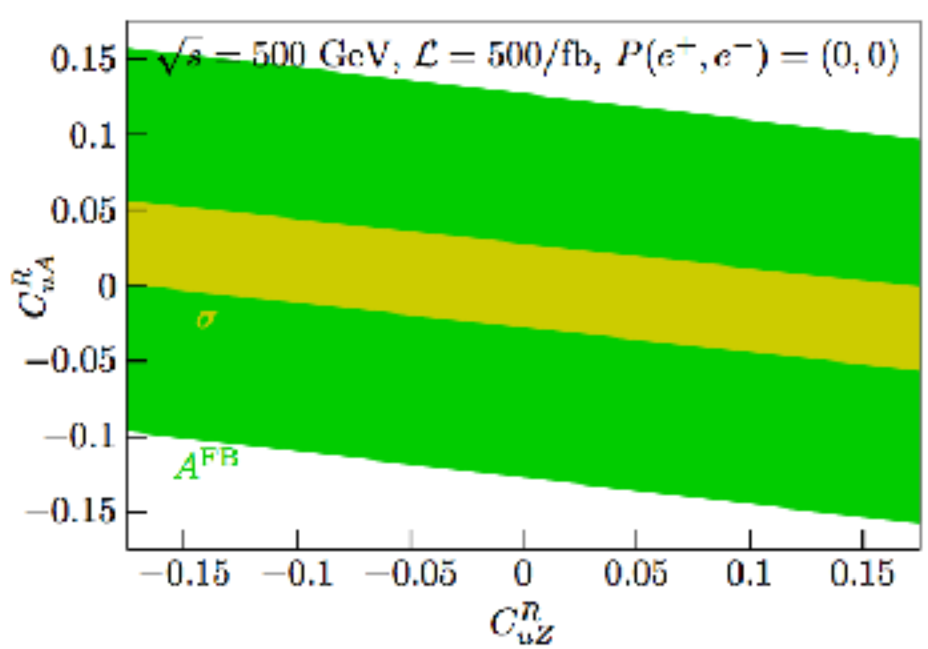
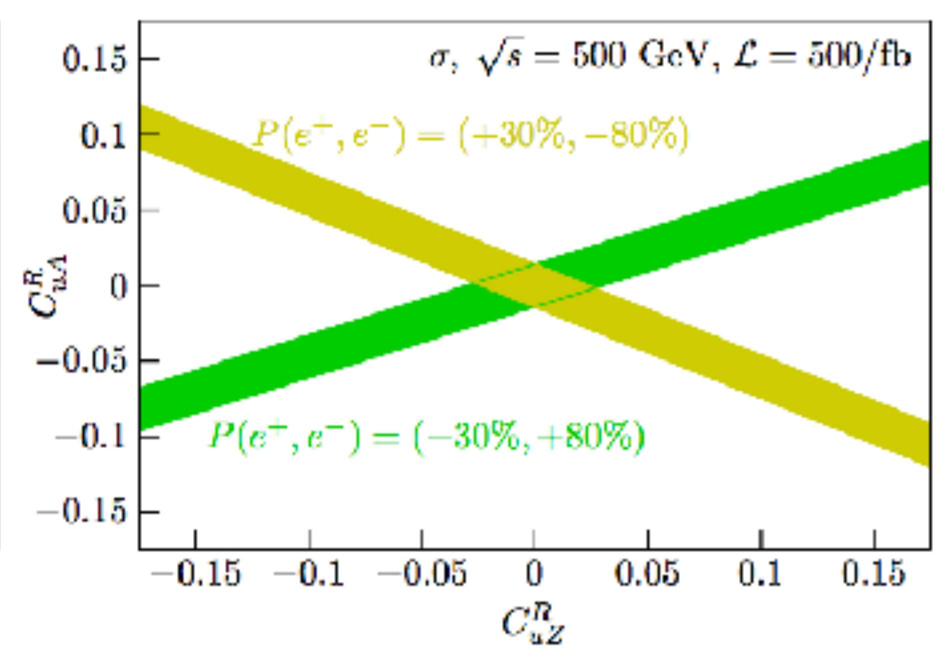


Forward-backward asymmetry



Role of beams polarization:





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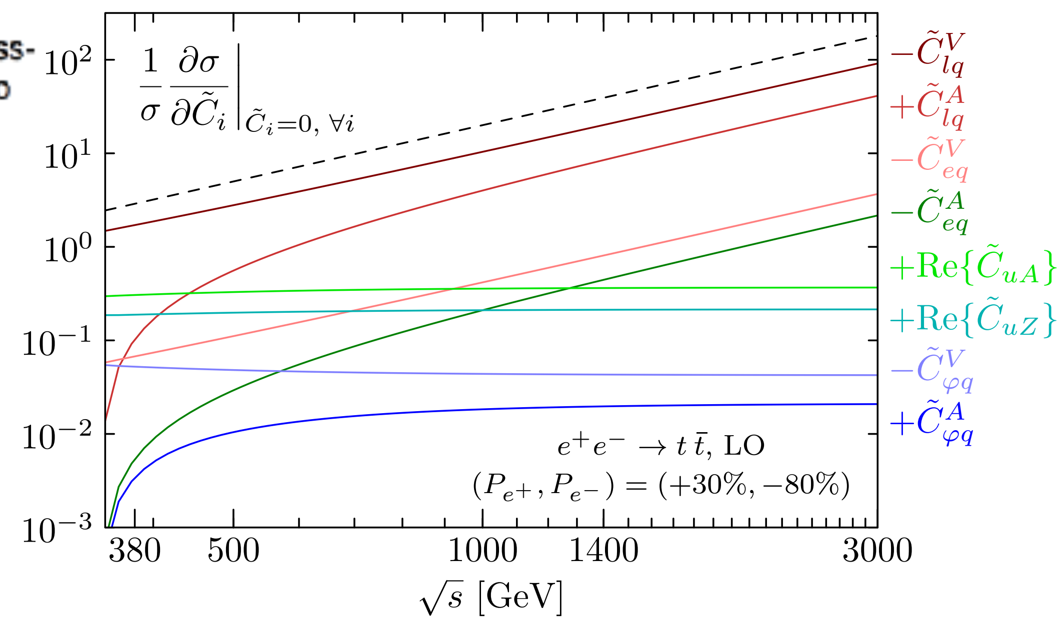
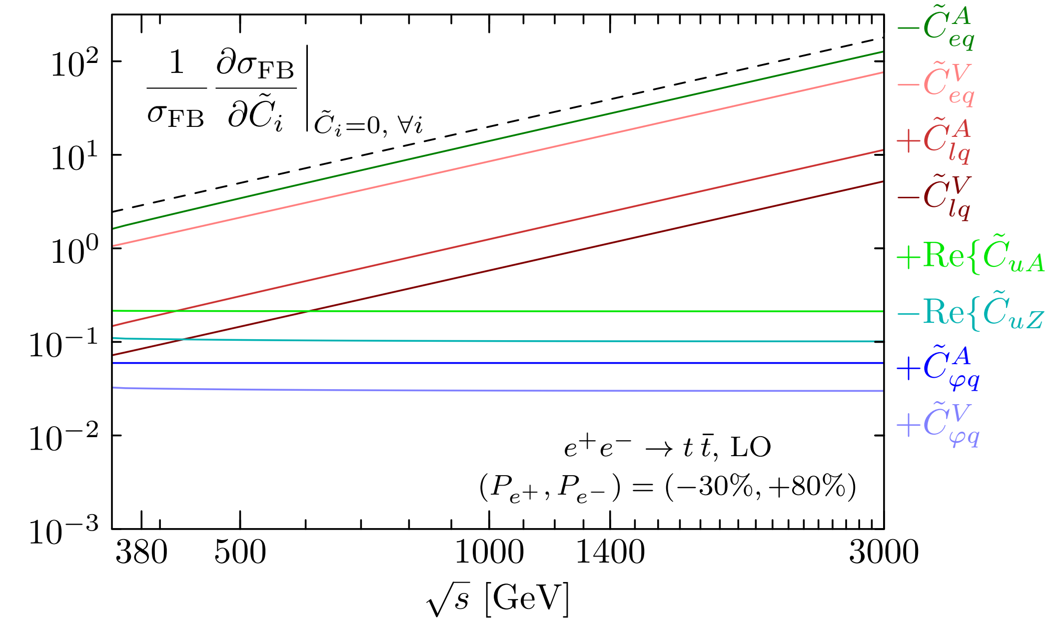
$\Delta\sigma\,(C)\,/\,\sigma\,/\,\Delta C$

Cross-section



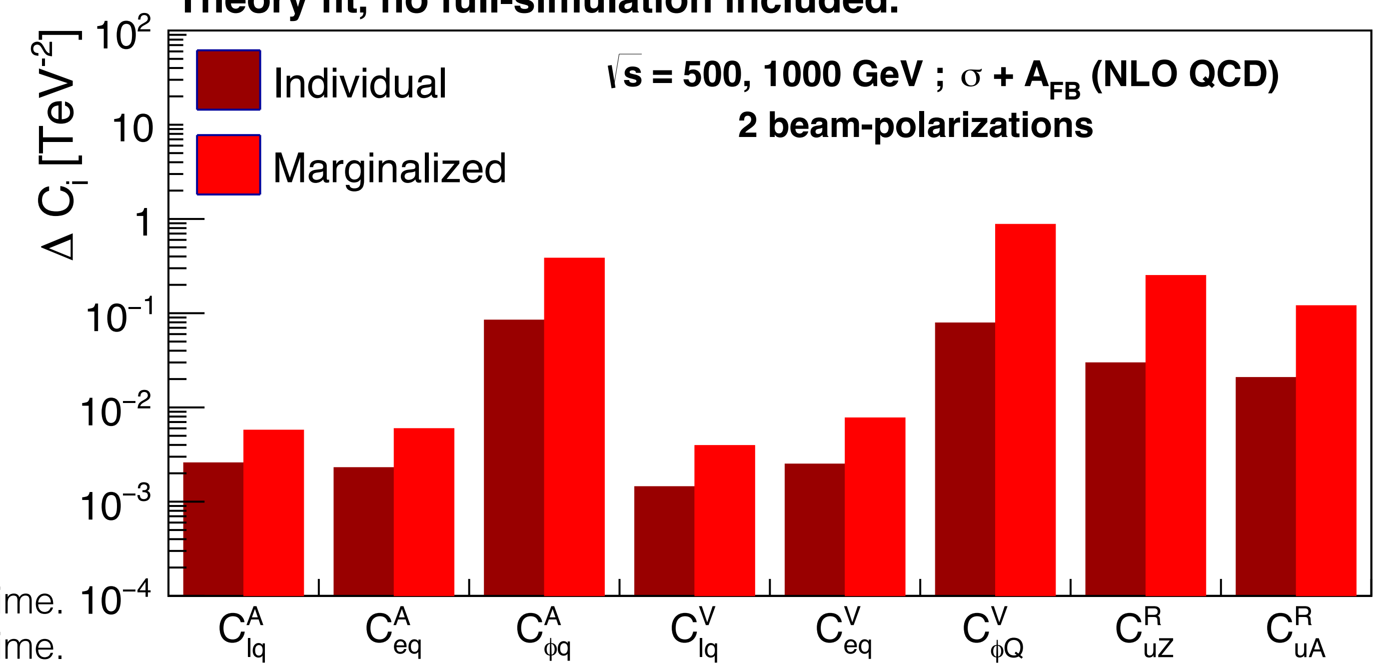
Forward-backward asymmetry



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

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

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

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

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

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

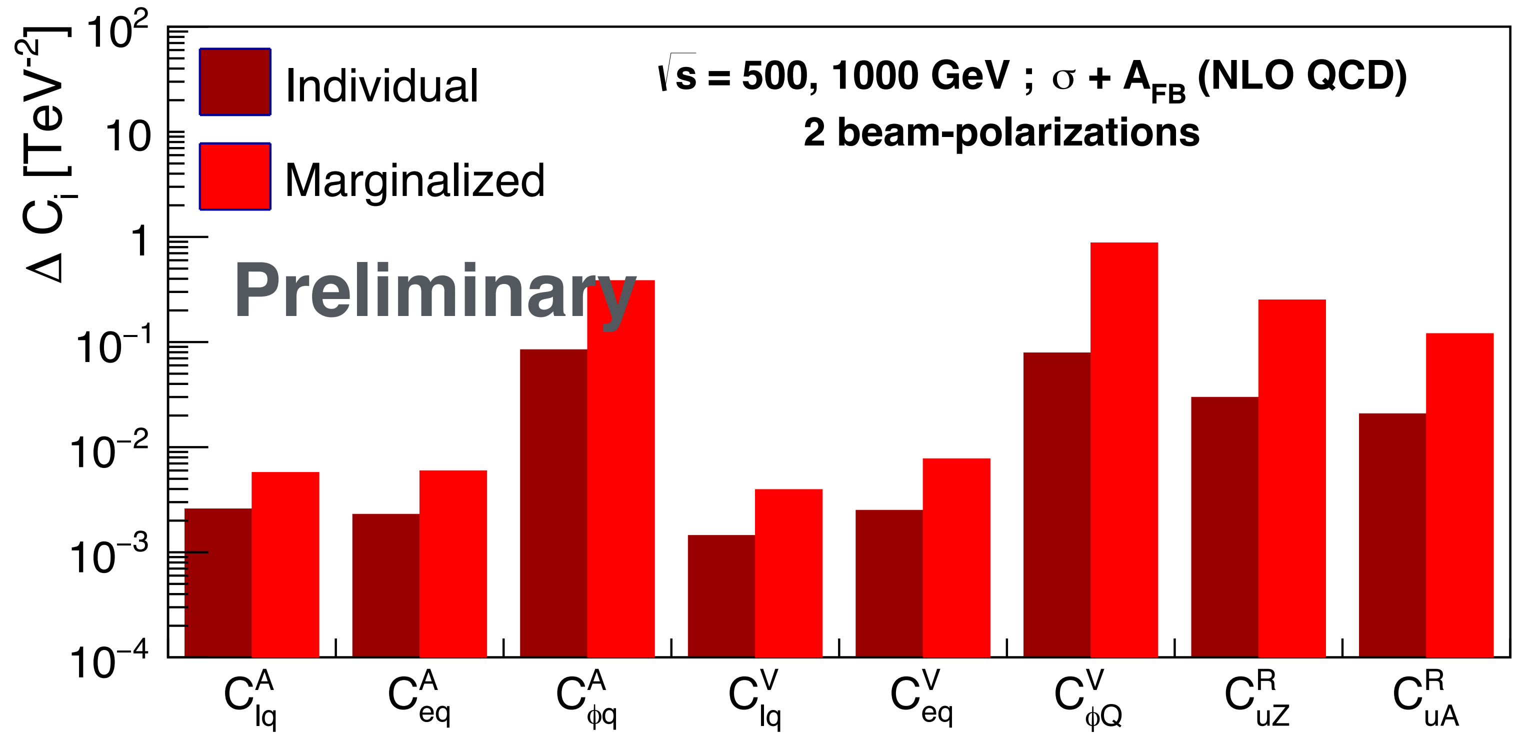
$$\mathcal{A}^{Im} = \langle \mathcal{O}_+^{Im} \rangle - \langle \mathcal{O}_-^{Im} \rangle = \boxed{\tilde{c}_\gamma(s)}\mathrm{Im}F_{2A}^\gamma + \boxed{\tilde{c}_Z(s)}\mathrm{Im}F_{2A}^Z$$

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

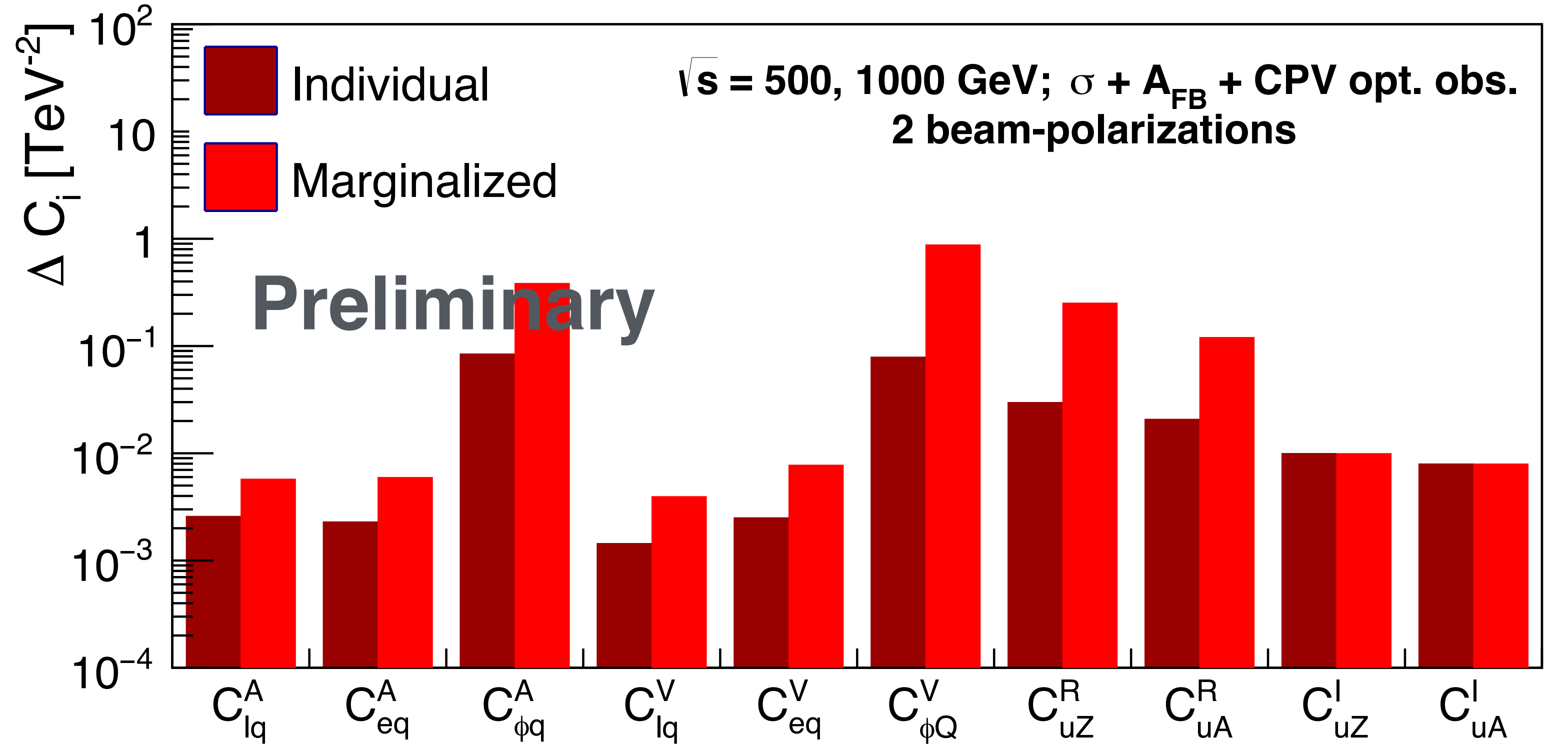
CPV observables in the global fit arXiv:1710.06737

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.

Statistically optimal observables

G. Durieux @TopLC 2017:

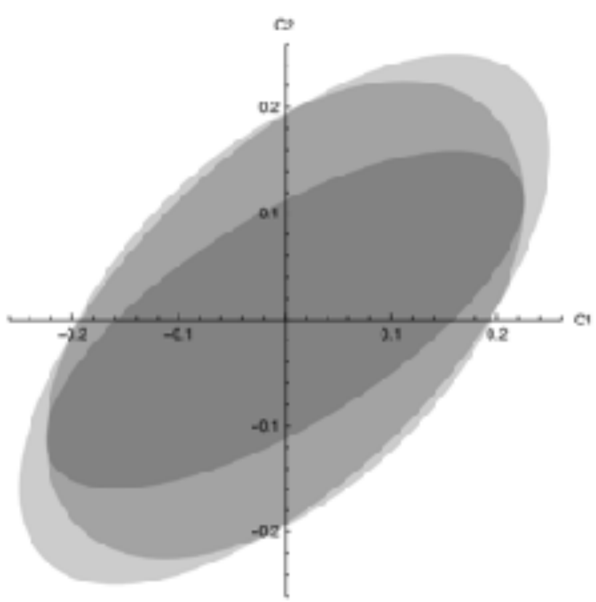
https://indico.cern.ch/event/595651/contributions/2573918/

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: $O_i(\Phi) = \sigma_i(\Phi)/\sigma_0(\Phi)$.



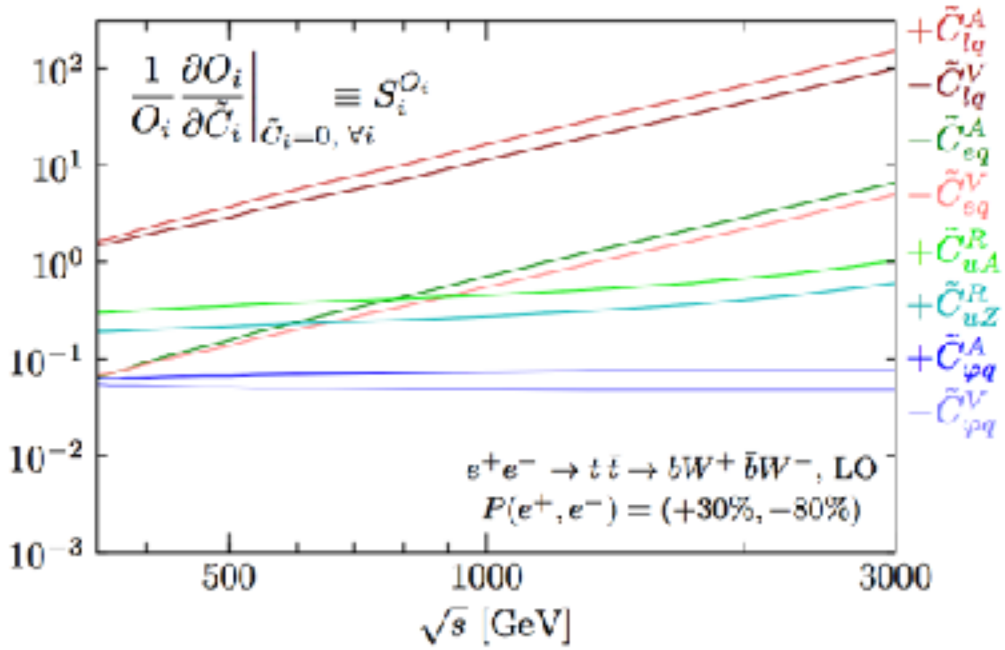
e.g. $\sigma(\phi) = 1 + \cos(\phi) + C_1 \sin(\phi) + C_2 \sin(2\phi)$

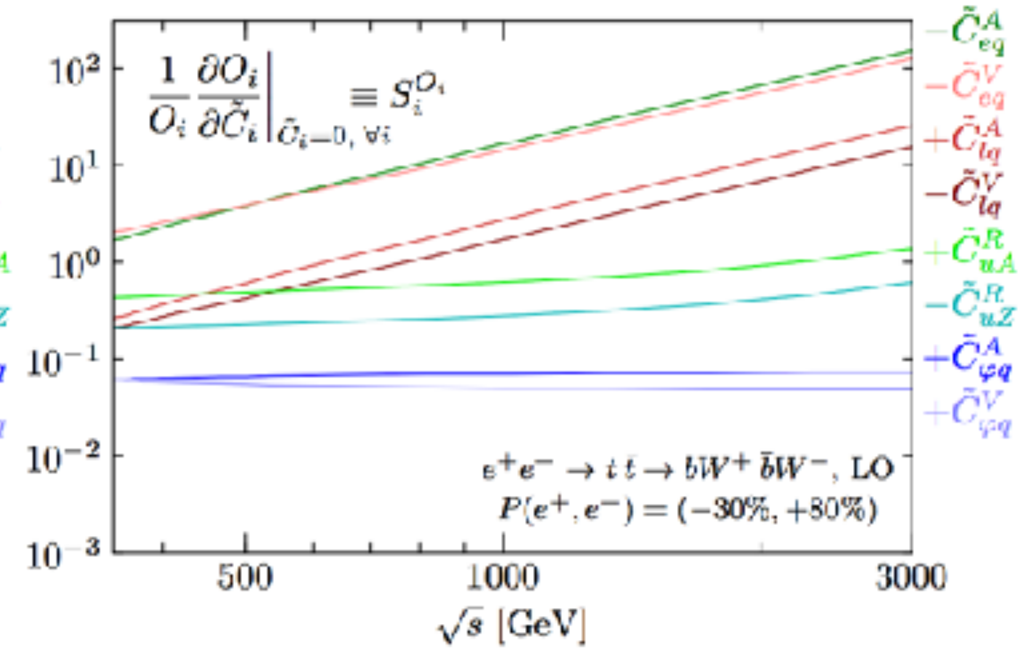
1. asymmetries: $O_i \sim \text{sign}\{\sin(i\phi)\}$
2. moments: $O_i \sim \sin(i\phi)$
3. statistically optimal: $O_i \sim \dfrac{\sin(i\phi)}{1+\cos\phi}$

$\Longrightarrow$ 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]

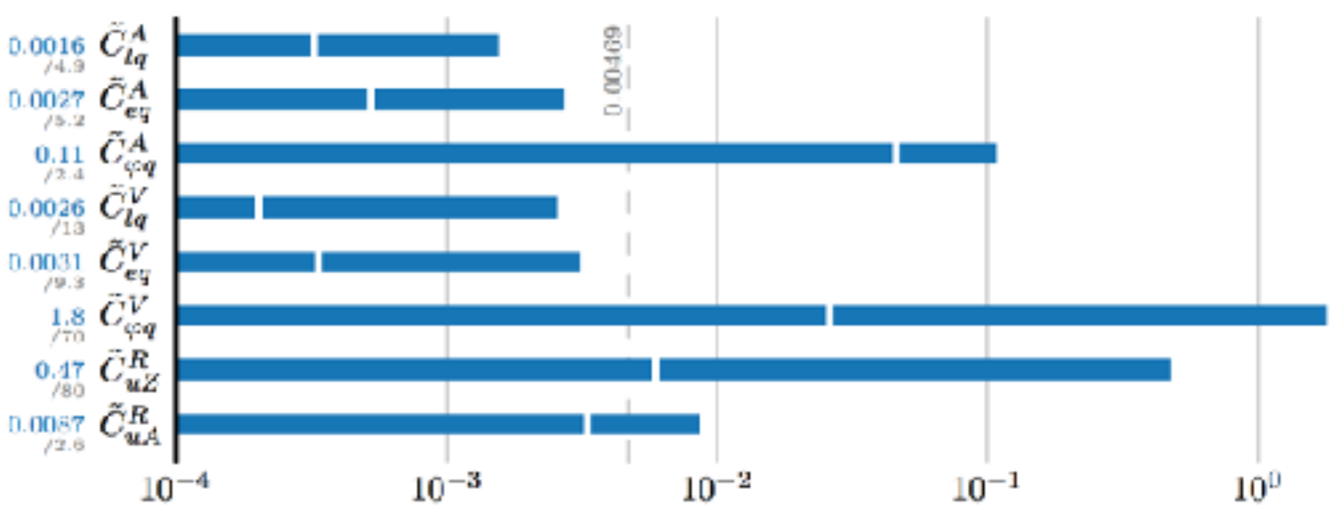
Statistically optimal observables sensitivities



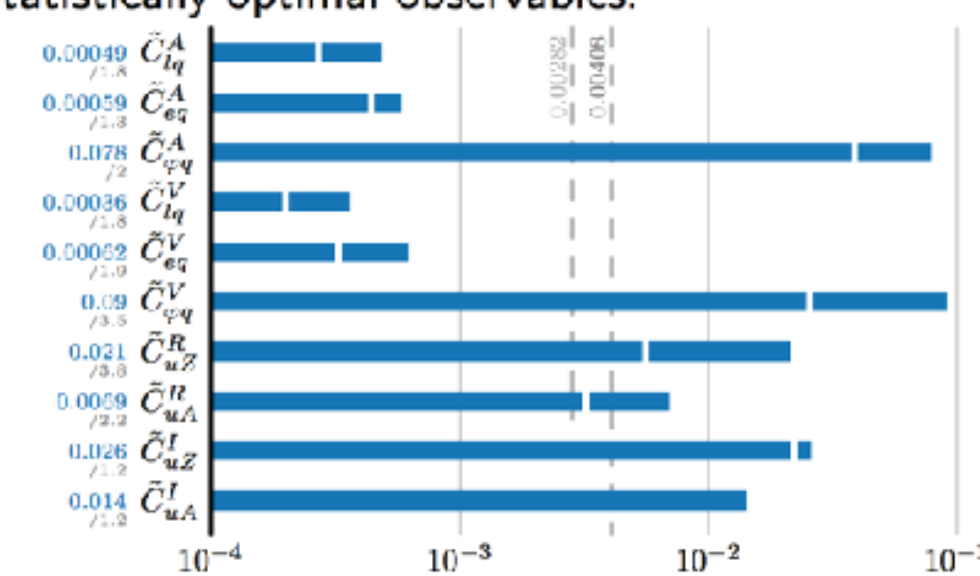


Comparison in the global limits (500GeV + 1TeV for 2 pols.):

$\sigma + A_{FB}$



Statistically optimal observables:

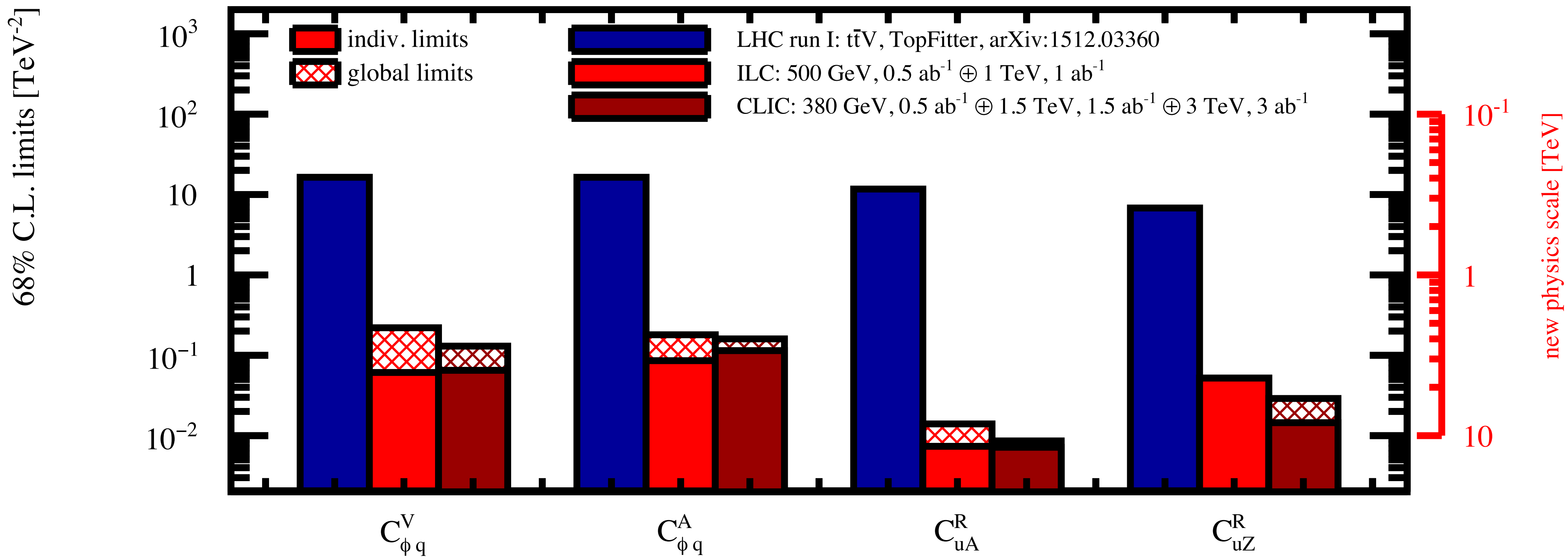


- **Even better individual limits**
- **Global limits within a factor 1.3 to 3.5**

Comparison with the LHC

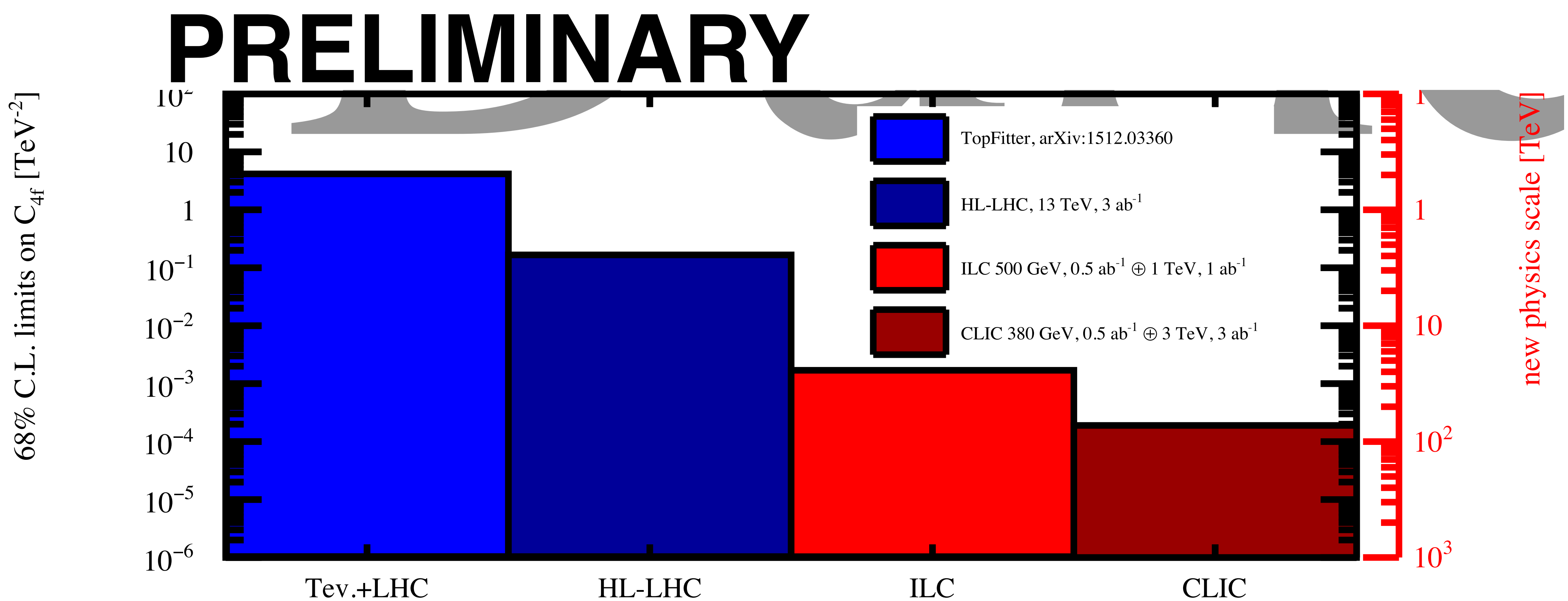
Comparison with the LHC: vertices

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).

Conclusions

- Cross-section + A_{FB} are not enough for global EFT fit.
- CP-odd operators well constrained by CP-odd optimal observables.
- 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

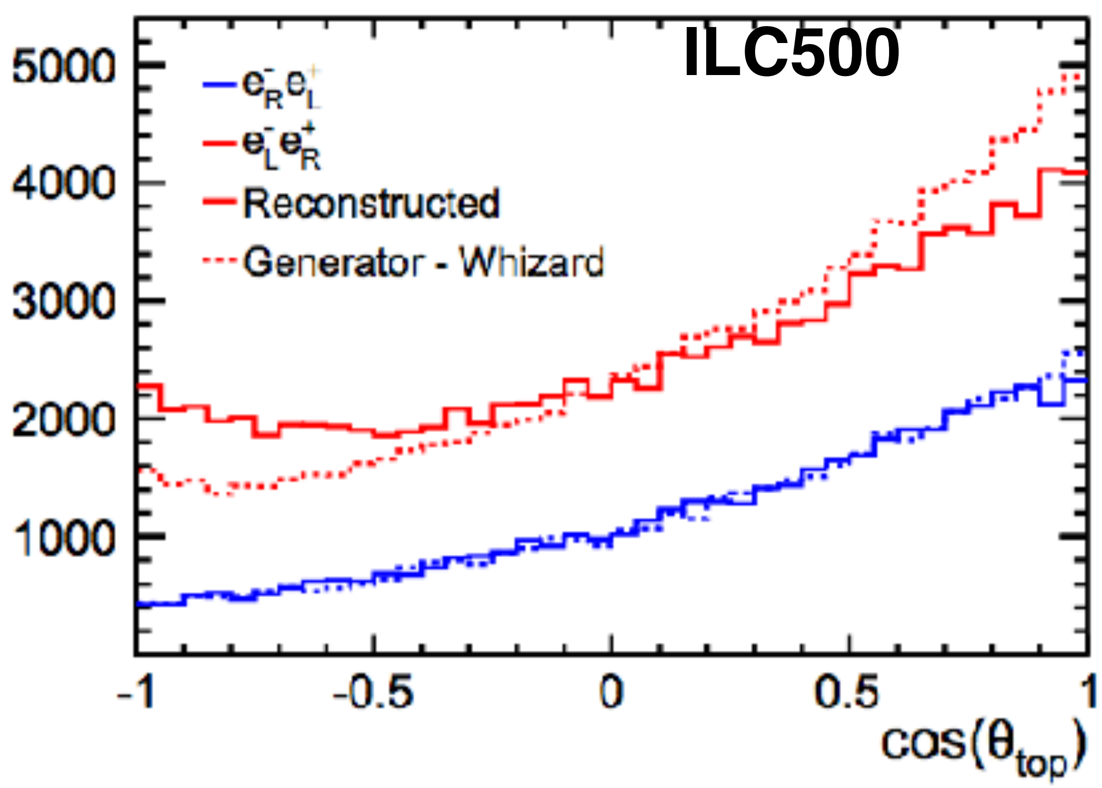
Full-simulation

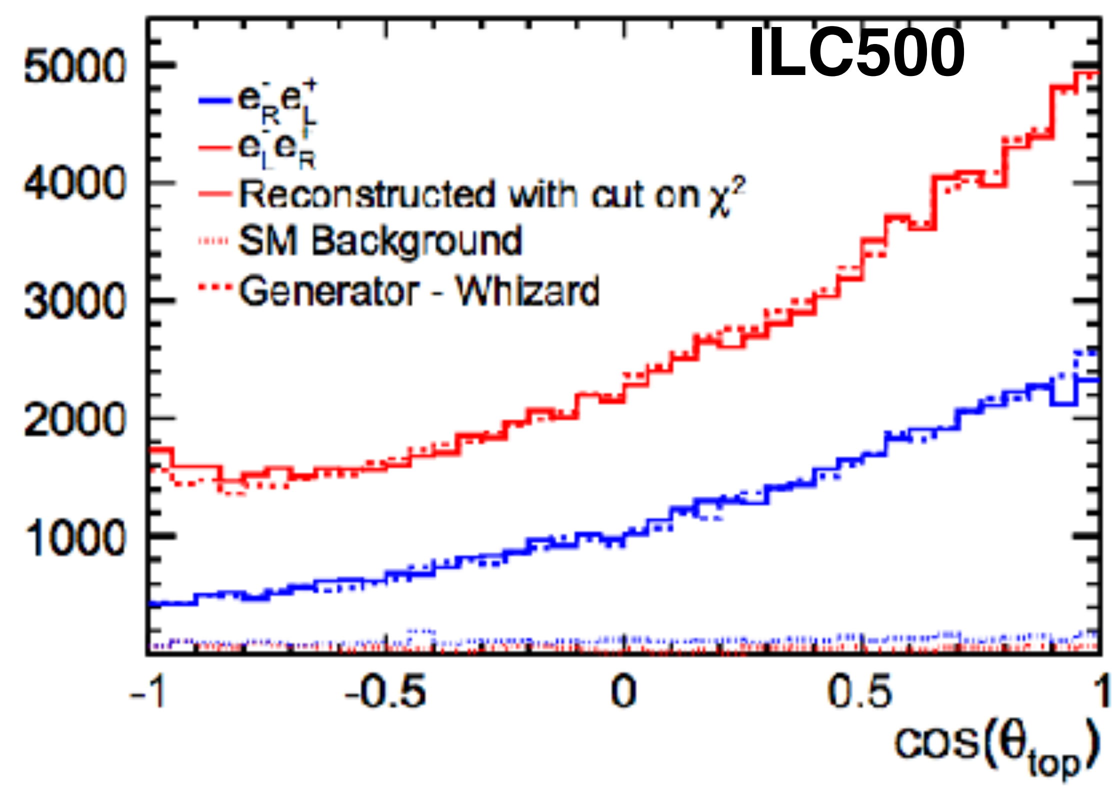
Full-simulation: low energies

Studies at CLIC380 and ILC500 included in I. Garcia thesis
(https://cds.cern.ch/record/2239794?ln=en)

- **Resolved analysis for a semileptonic tt decay** - Production near threshold (lower effective centre-of-mass due to ISR, beamstrahlung), use b-tagging, search for W, or 3 jets with a combined invariant mass near m_t

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





Full-simulation: low energies

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- **Resolved analysis** - Production near threshold (lower effective centre-of-mass due to ISR, beamstrahlung), use b-tagging, search for W, or 3 jets with a combined invariant mass near m_t

Results for CLIC380 have been revisited for the CLICdp top paper

CLIC@380GeV L=500fb^{-1}

$\sqrt{s}$	380 GeV[a]	
P(e$^-$)	-80%	+80%
$\sigma_{t\bar{t}}$ [fb]	161.00	75.97
stat. unc. [fb]	1.04	0.75
A_{FB}	0.1761	0.206
stat. unc.	0.0090	0.0085

CLICdp Preliminary

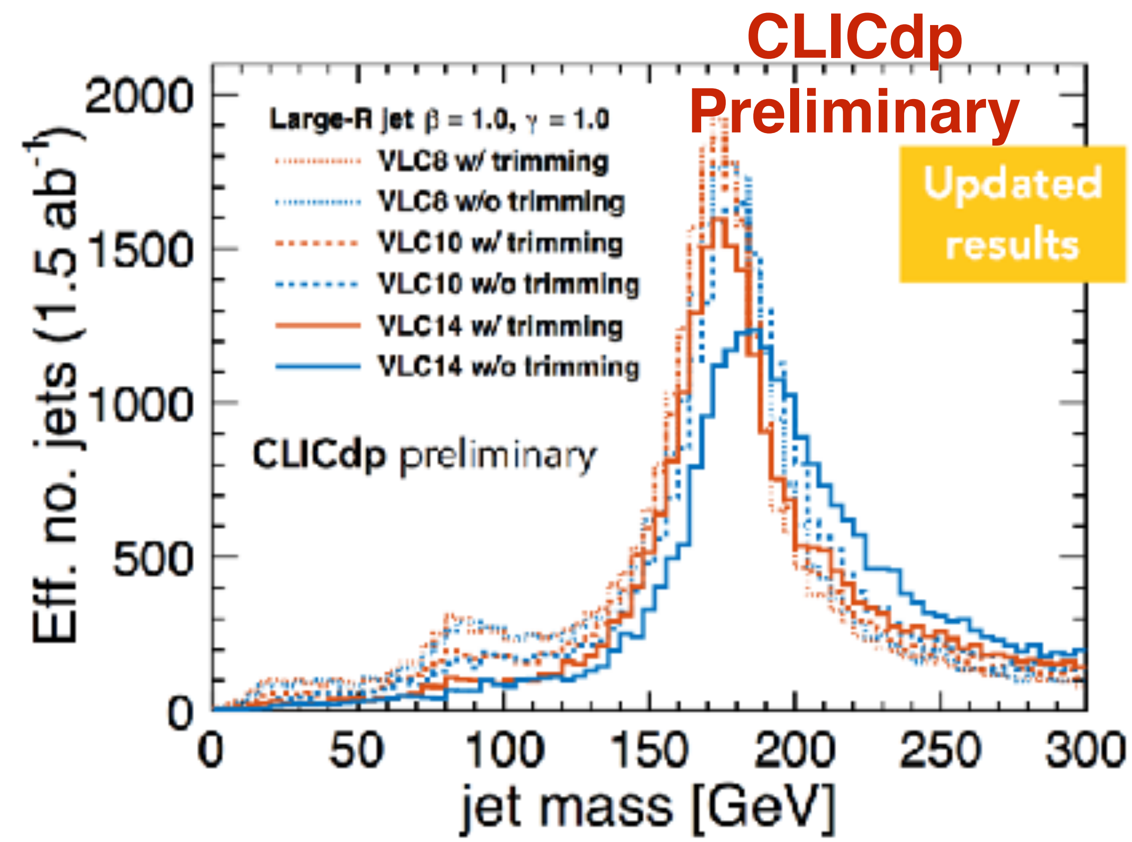
ILC@500GeV L=500fb^{-1} [arXiv:1505.06020]

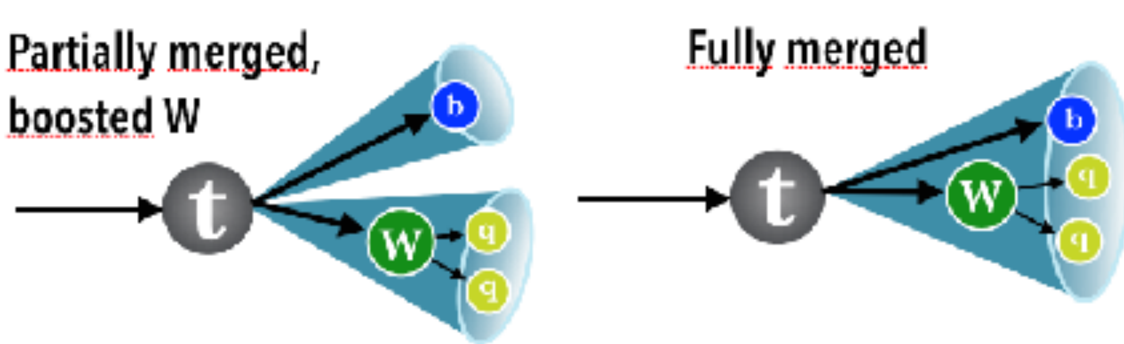
$\mathcal{P}_{e^-}, \mathcal{P}_{e^+}$	$(\delta\sigma/\sigma)_{\text{stat.}}$ (%)	$(\delta A^t_{FB}/A^t_{FB})_{\text{stat.}}$ (%)
$-0.8, +0.3$	0.47	1.8
$+0.8, -0.3$	0.63	1.3

Full-simulation: high energies

- Collimated decay products - Identify and correctly assign the top decay products
- **Boosted analysis -** Standard identification techniques may not work: b-tagging not foreseen, tracks are very close to each other, W decay products not isolated from each other or b-jet,
    - Idea: tag tops by identifying prongy sub-structure

Optimization in jet clustering parameters
Fully-hadronic decay mode reconstruction

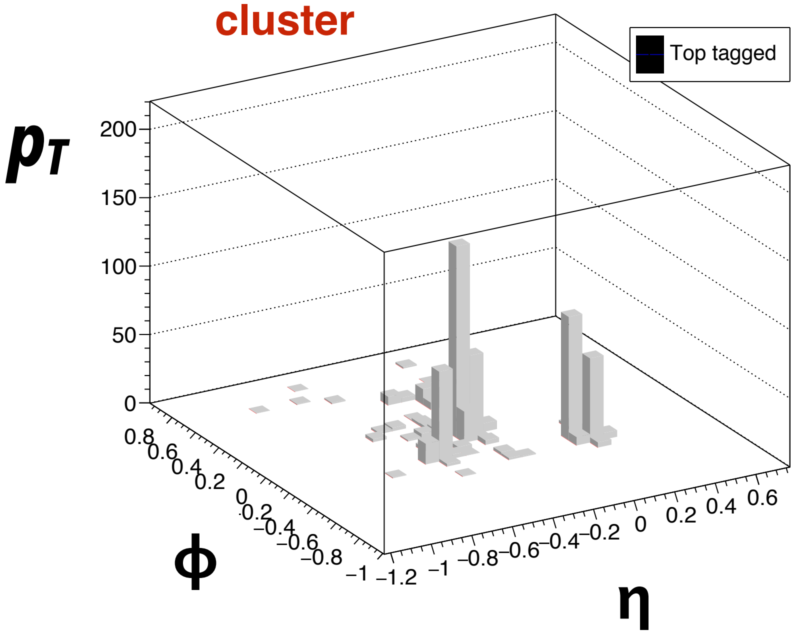


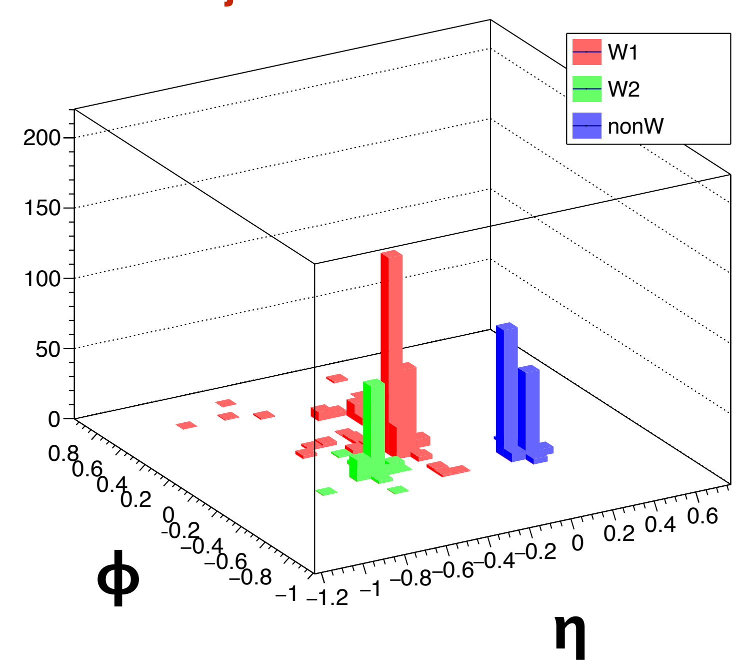


- Jet clustering (incl. trimming)
    - 2 exclusive large-R jets
- Jet tagging:
    - Parsing sub-structure
- Flavour-tagging (sub-jet, fat-jet)

Parsing sub-structure

Jet de-clustering (FastJet extension), **DOI: 10.1103/PhysRevLett.101.142001**

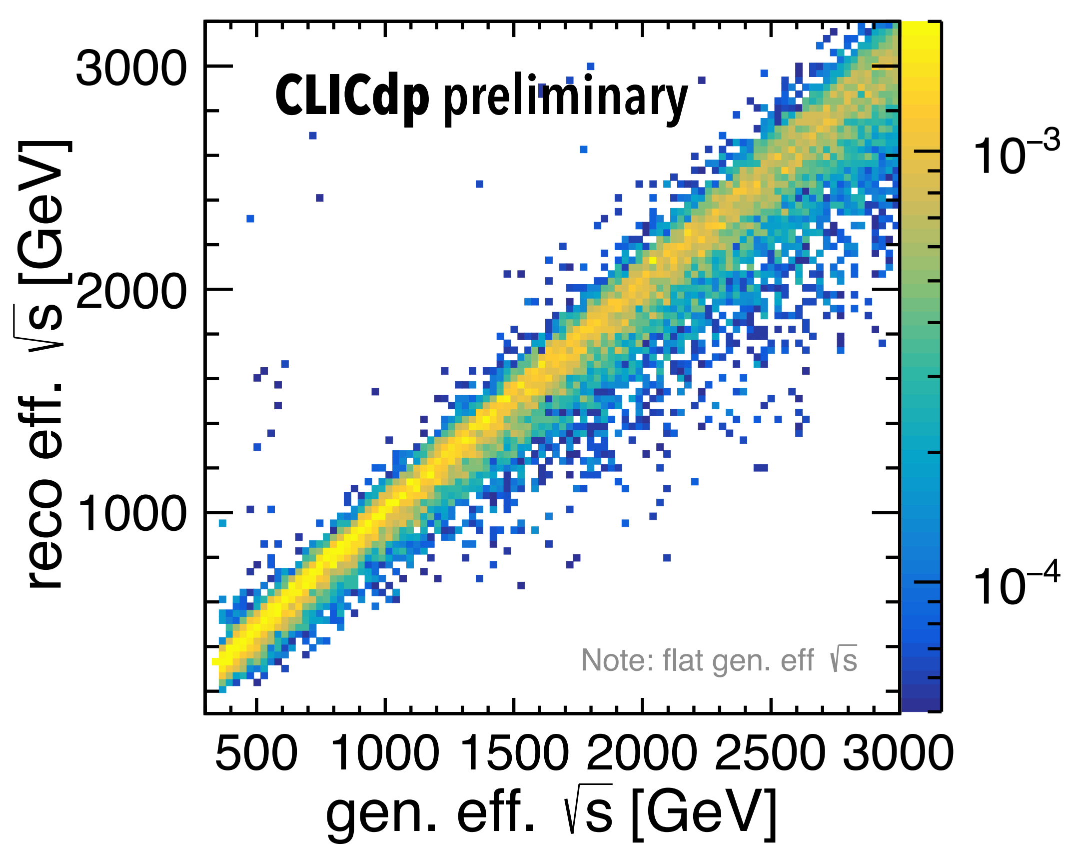




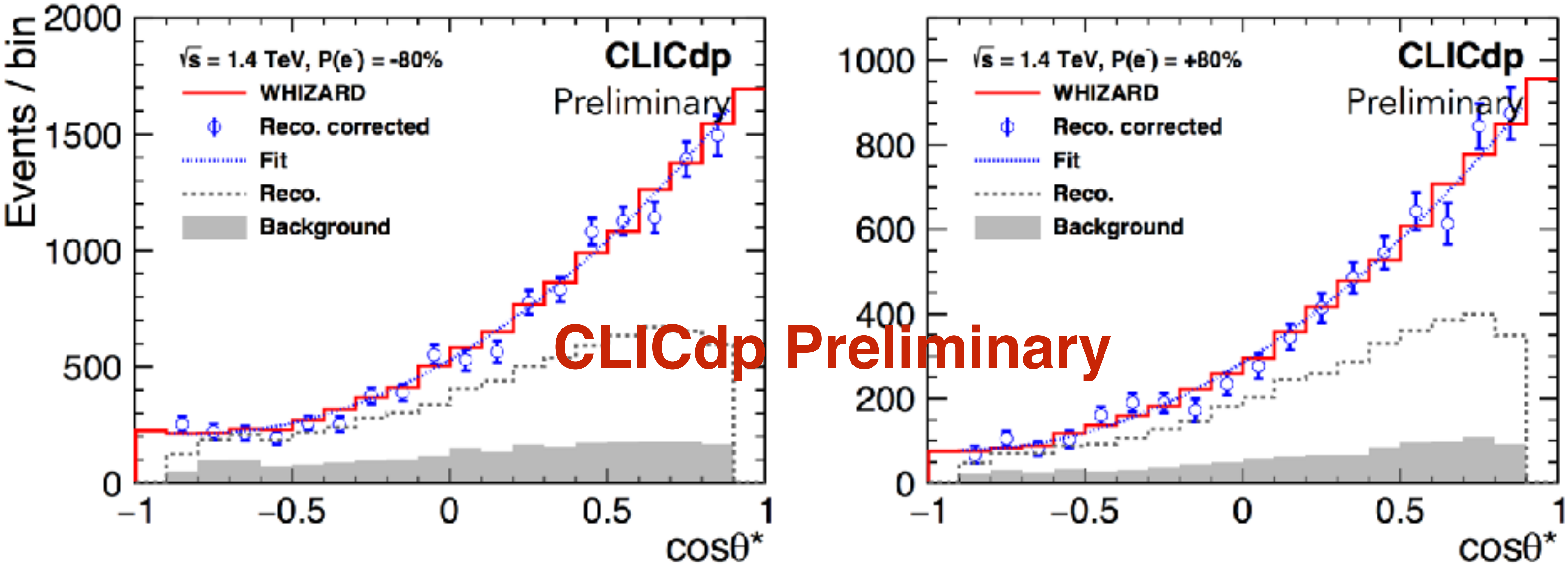
- VLC jet clustering algorithm (R=1.5, β=1, γ=1) + trimming
- "JH Top Tagger"
- kinematic cuts ($m_t \in [145,205]$ GeV, $m_W \in [65,95]$ GeV)

Event selection

- Technical cut (gen. level) in √s' (same cut can be done at reconstruction level)
- 1 isolated lepton, 1 top tagged jet ("JH Top Tagger")
- Flavour tagging (fat-jet / sub-jet) → BDT
- Exploiting kinematics of semi-leptonic side → BDT



Full-simulation: high energies



Numerical results will appear soon in the CLICdp top quark paper

Some technical numbers at reconstruction
https://cds.cern.ch/record/2239794?ln=en

CLIC380 (Repository https://twiki.cern.ch/twiki/bin/view/CLIC/MonteCarloSamplesForTopPhysics)

- Jet clustering: VLC algorithm (R=1.6, β = 0.8, γ = 0.8).

ILC500

- Jet clustering: VLC algorithm (R=1.2, β = 0.8, γ = 0.8).

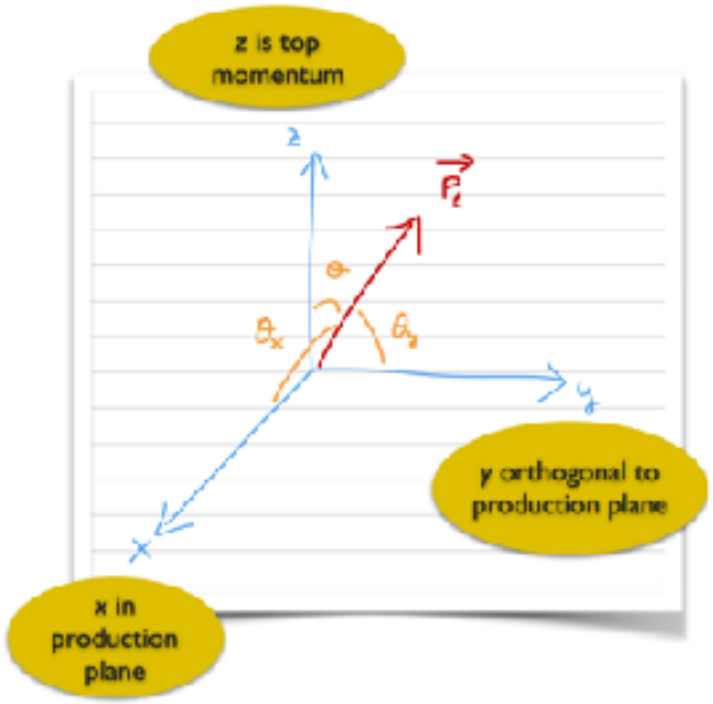
Collider	**ILC**	**CLIC**
Sample	$e^+e^- \rightarrow l^\pm \nu b\bar{b}q'\bar{q}$	$e^+e^- \rightarrow 6f$ ($t\bar{t}$ compatible)
$\sqrt{s}$ [GeV]	500	380
Luminosity [fb^{-1}]	500	500
$P(e^-), P(e^+)$	$\mp 1, \pm 1$	$\mp 0.8, 0$
Detector model	ILD_o1_v05 [54]	CLIC_ILD_CDR [53]
Number of BX	1	300
Background	1.7 $\gamma\gamma \rightarrow$ hadrons / BX	0.0464 $\gamma\gamma \rightarrow$ hadrons / BX

[53] L. Linssen, A. Miyamoto, M. Stanitzki and H. Weerts, Physics and Detectors at CLIC: CLIC Conceptual Design Report, 1202.5940.
[54] H. Abramowicz et al., The International Linear Collider Technical Design Report - Volume 4: Detectors, 1306.6329.

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

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

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

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

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

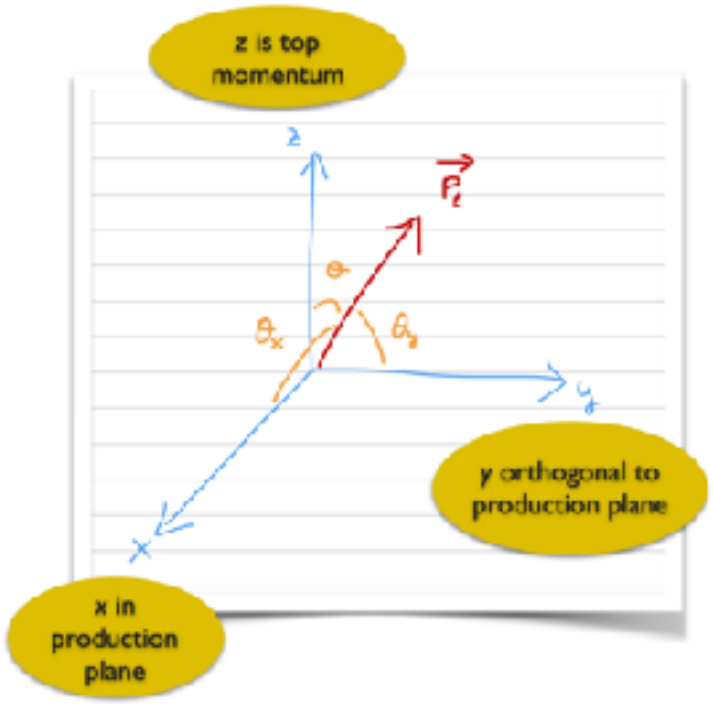
Overlapping with the forward-backward asymmetry.

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.

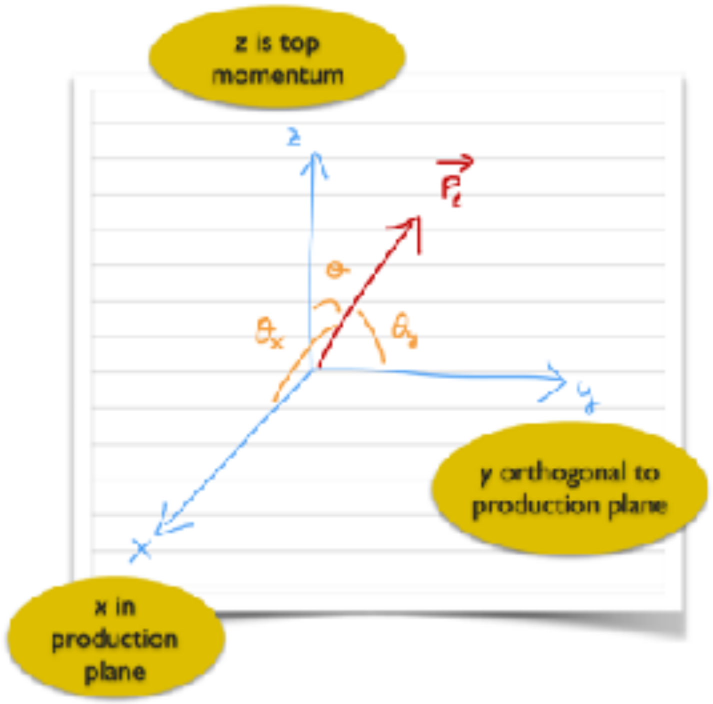
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_i} = \frac{1}{2}(1+\alpha_i P\cos\theta_i)$$

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

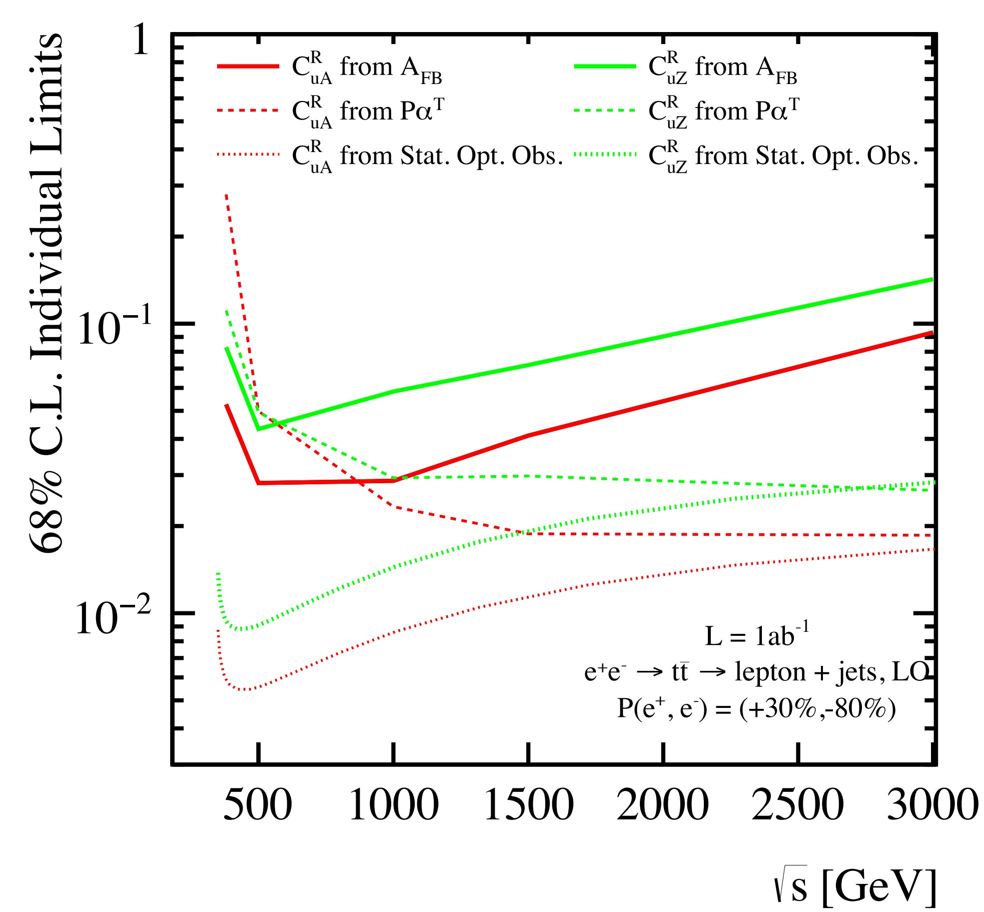
$$e^-e^+ \to t\bar{t} \to W^+bW^-\bar{b} \to l\nu b\bar{b}q\bar{q}$$

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

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

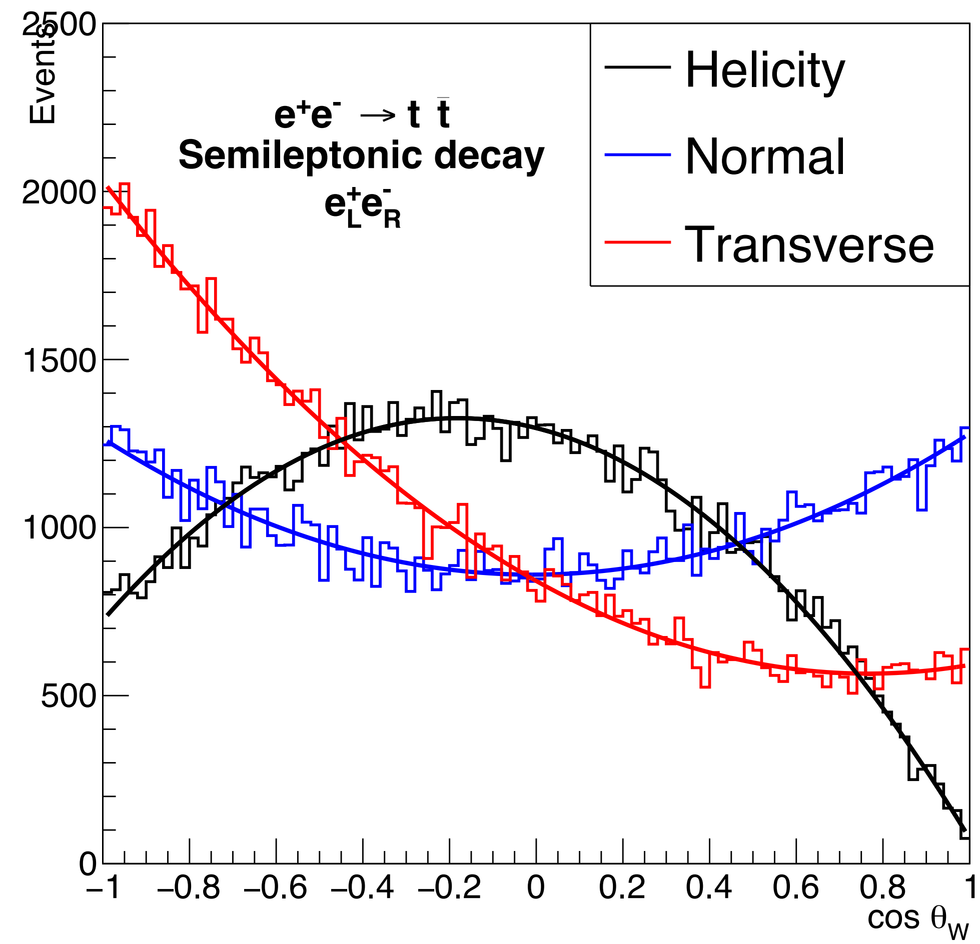
$$O^3_{\varphi q} \equiv \frac{y_t^2}{2} \;\; \bar{q}\tau^I \gamma^\mu q \;\; \varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi$$

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

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

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

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

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

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

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

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

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

AT is proportional to the top quark transverse polarization

- Oϕud 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

CPV backup

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**

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

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

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

CPV: Coefficients vs sqrt(s)

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

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

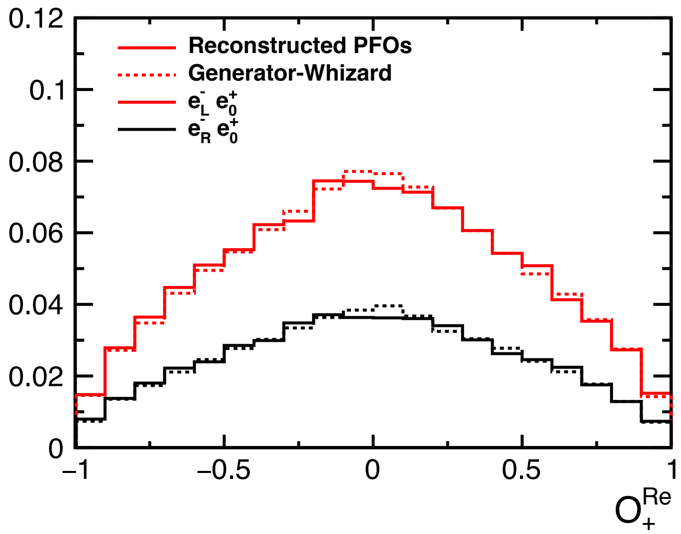
c.m. energy $\sqrt{s}$ [GeV]	$c_\gamma(s)$	$c_Z(s)$	$\tilde{c}_\gamma(s)$	$\tilde{c}_Z(s)$
380	0.245	0.173	0.232	0.164
500	0.607	0.418	0.512	0.352
1000	1.714	1.151	1.464	0.983
1400	2.514	1.681	2.528	1.691
3000	5.589	3.725	10.190	6.791

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

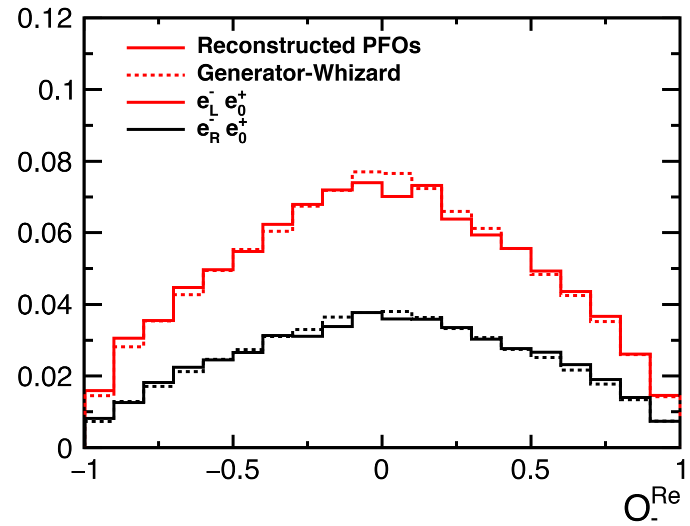
c.m. energy $\sqrt{s}$ [GeV]	$c_\gamma(s)$	$c_Z(s)$	$\tilde{c}_\gamma(s)$	$\tilde{c}_Z(s)$
380	-0.381	0.217	0.362	-0.206
500	-0.903	0.500	0.761	-0.422
1000	-2.437	1.316	2.081	-1.124
1400	-3.549	1.909	3.569	-1.920
3000	-7.845	4.205	14.302	-7.667

Thanks to Bernreuther

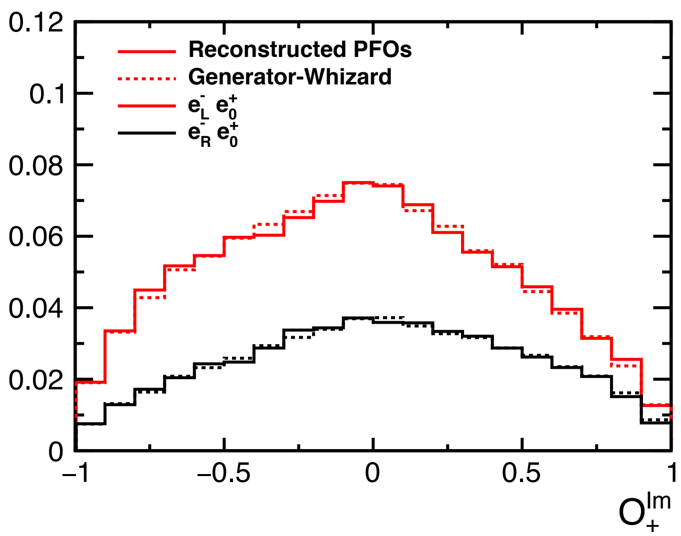
CPV: Full-simulation: CLIC@380GeV



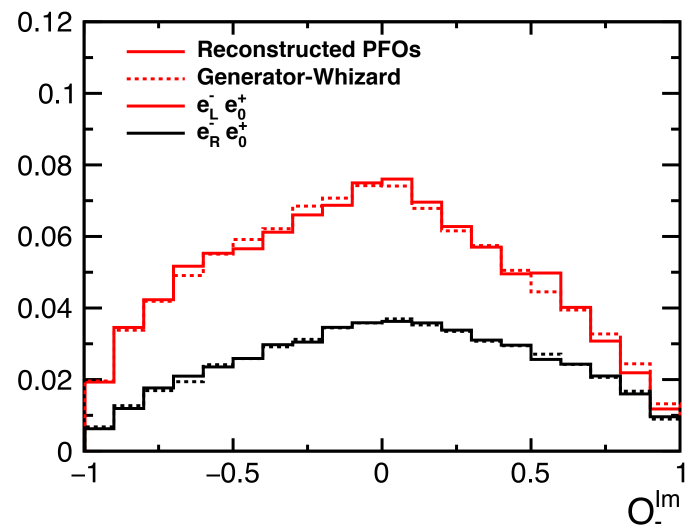
(a) $\mathcal{O}^{Re}_+$



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



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



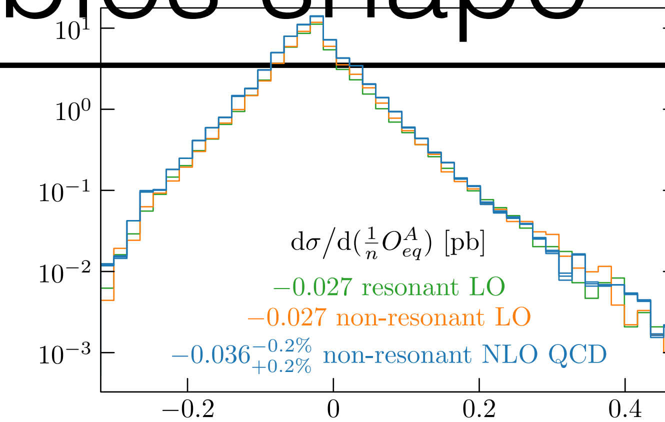
(d) $\mathcal{O}^{Im}_-$

polarization	e^-_L ($P_{e^-} = -0.8$)	e^-_R ($P_{e^-} = +0.8$)
$\mathcal{A}^{Re}$	-0.00006 ± 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

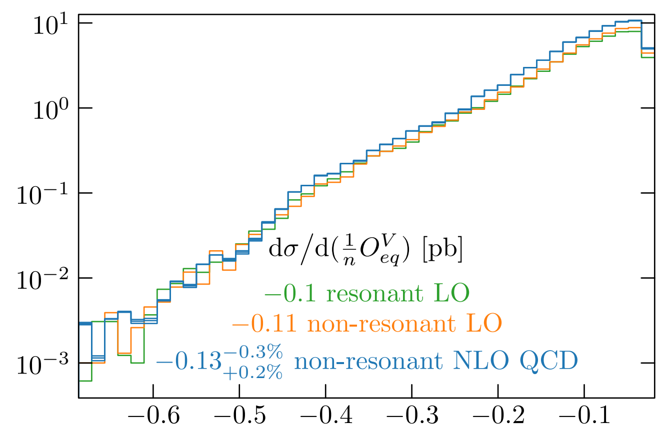
Statistically optimal observables shape

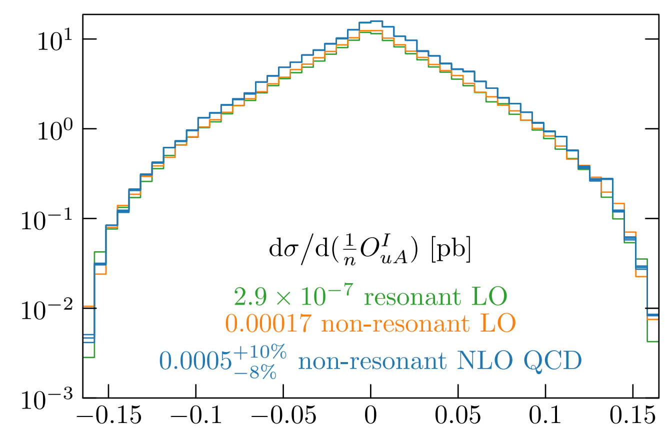
Example for 500 GeV (e-, e+) = (-0.8, 0.3)

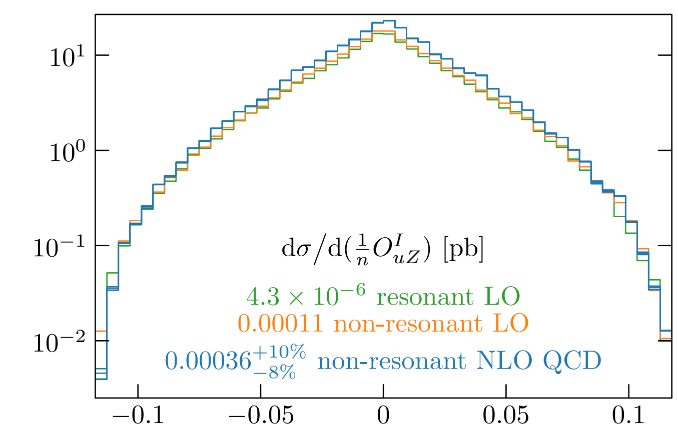


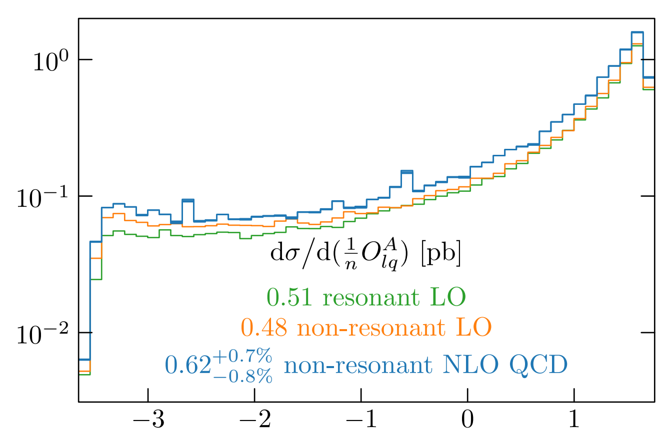
Theory uncertainties under study

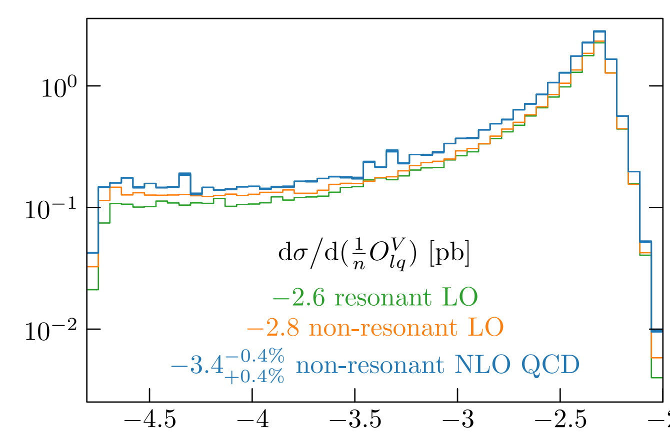
Generated plots

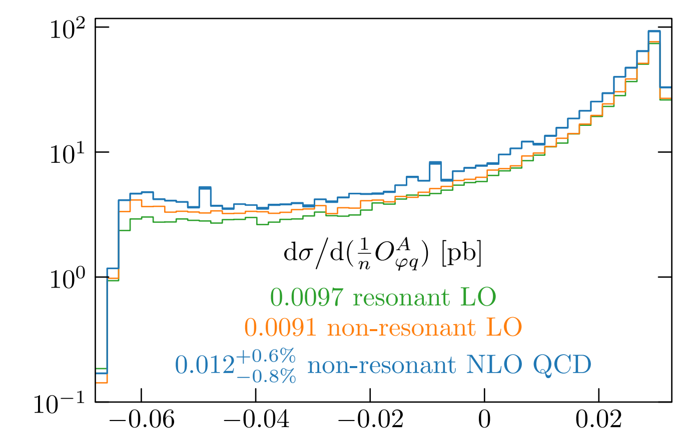


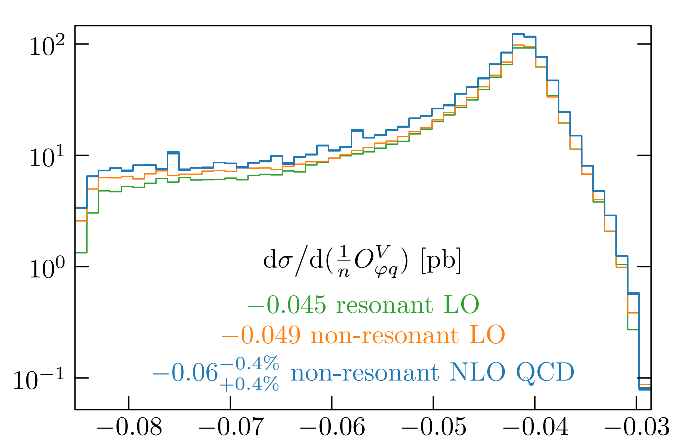


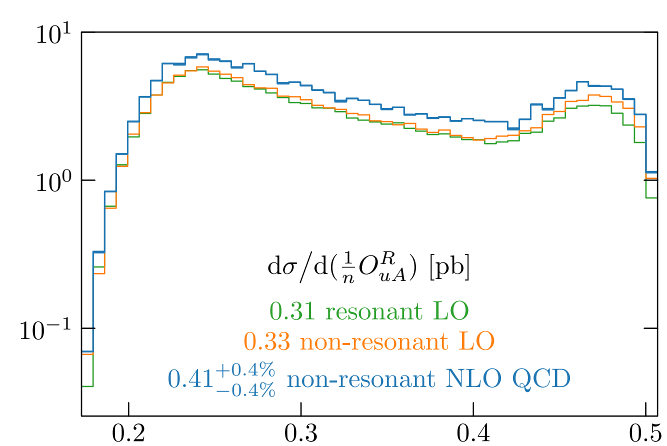


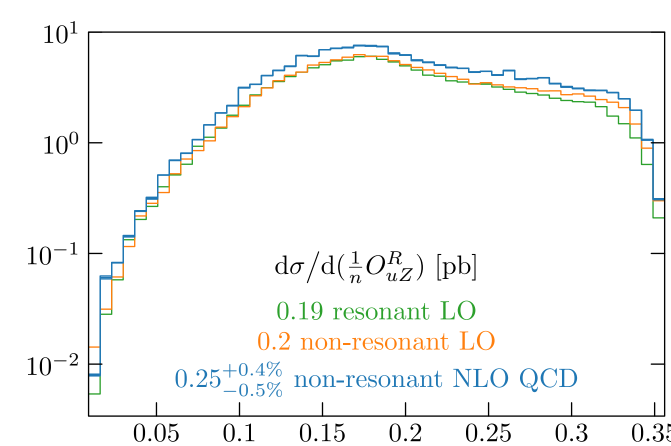








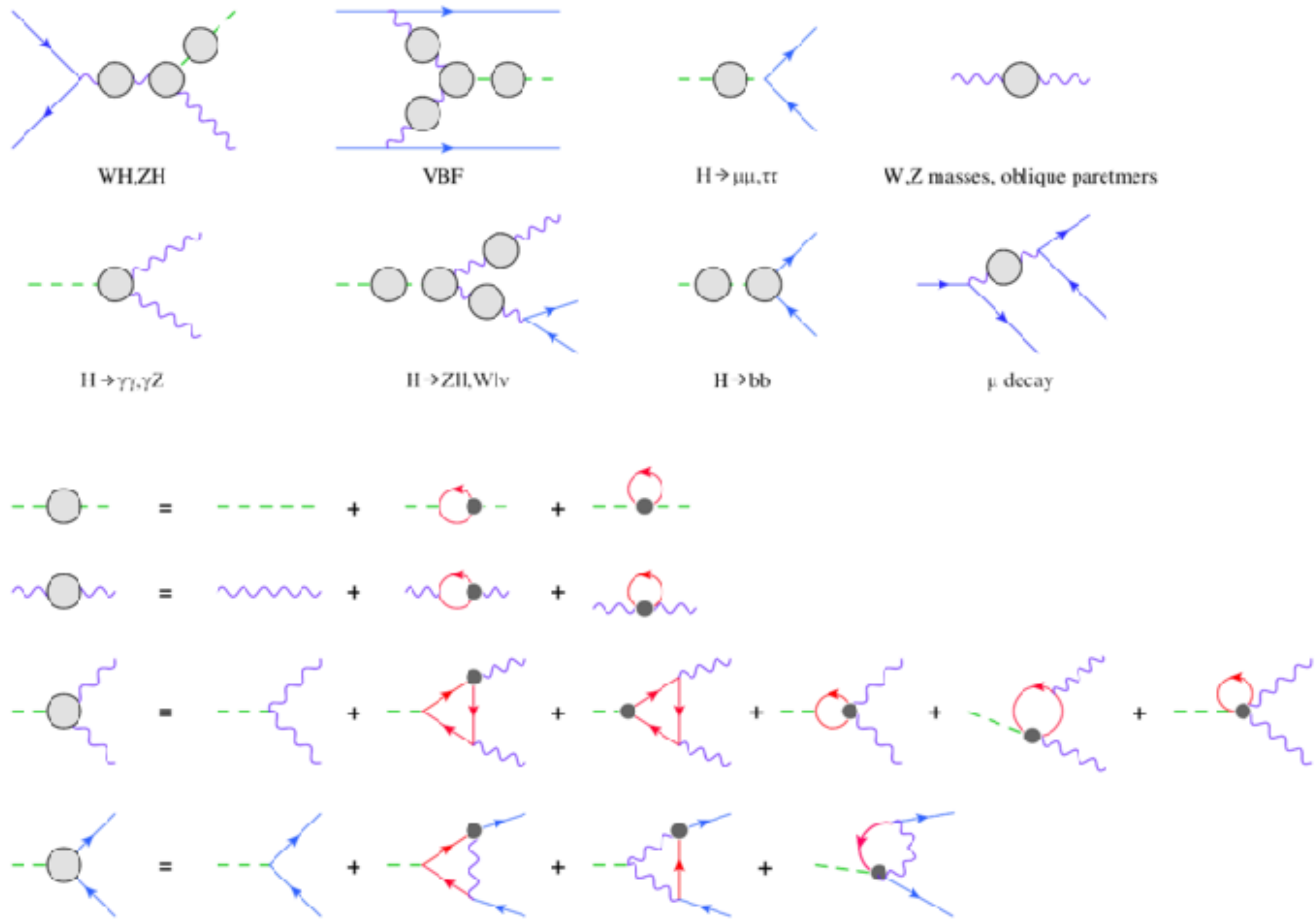




Ongoing work at KEK

Dimension-six electroweak top-loop effects in Higgs production and decay

C. Zhang and E. Vryonidou (arXiv:1804.09766)



Ongoing work at KEK

- **First success**: introduce numbers by Cen and Eleni to the Higgs global fit program.
- **Expected conclusion**: to add top-quark operators to the Higgs fit is not good for Higgs couplings uncertainties.
- Studied (but not yet interpreted) the impact of adding top quarks operators one by one to the fit.
- **Future**: try to collaborate with the authors of the paper and discuss deeply next steps.