Top EW coupling measurements at a linear collider

Americas workshop on linear colliders, SLAC, June 2017

Martín Perelló, Marcel Vos (IFIC, UVEG/CSIC, Valencia)

Reporting on EFT work in collaboration with Gauthier Durieux and Cen Zhang
CPV work in collaboration with Werner Bernreuther, Long Chen, François Richard

Outline

Towards a global fit of top measurements at a linear collider

Extending the interpretation: effective field theory vs. form factors

Extending the analysis to CP violating observables

Extending to complete programme, including high-energy operation

Extending the set of measurements (polarization, top width, $b\bar{b}$, …)

Preliminary results …

EFT for top physics

Talks by Francesco Riva, Jorge de Blas, Michael Russell, J.A. Aguilar-Saavedra, Gauthier Durieux, Martín Perelló at LC top workshop, CERN, 2017

EFT

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

Express the impact of “any” BSM physics in terms of a finite number of D6 operators.

The future? An extensive programme of top measurements with exquisite BSM sensitivity. Interpretation in a global fit to D6 operator coefficients. At present: use EFT to “score” the BSM potential of different channels/machines.

LHC global fit

Buckley, Englert, Ferrando, Miller, Moore, MR, White (TopFitter): 1512.03360

Top quark LHC operators

$$\mathcal{O}_{qq}^{(1)} = (\bar{Q}\gamma_\mu Q)(\bar{Q}\gamma^\mu Q) \qquad \mathcal{O}_{uW} = (\bar{Q}\sigma^{\mu\nu}\tau^I u)\tilde{\varphi}W^I_{\mu\nu} \qquad \mathcal{O}_{\varphi q}^{(3)} = i(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi)(\bar{Q}\gamma^\mu\tau^I Q)$$

$$\mathcal{O}_{qq}^{(3)} = (\bar{Q}\gamma_\mu \tau^I Q)(\bar{Q}\gamma^\mu \tau^I Q) \qquad \mathcal{O}_{uG} = (\bar{Q}\sigma^{\mu\nu}T^A u)\tilde{\varphi}G^A_{\mu\nu} \qquad \mathcal{O}_{\varphi q}^{(1)} = i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\gamma^\mu Q)$$

$$\mathcal{O}_{uu} = (\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u) \qquad \mathcal{O}_G = f_{ABC}G^{A\nu}_\mu G^{B\lambda}_\nu G^{C\mu}_\lambda \qquad \mathcal{O}_{uB} = (\bar{Q}\sigma^{\mu\nu}u)\tilde{\varphi}B_{\mu\nu}$$

$$\mathcal{O}_{qu}^{(8)} = (\bar{Q}\gamma_\mu T^A Q)(\bar{u}\gamma^\mu T^A u) \qquad \mathcal{O}_{\tilde{G}} = f_{ABC}\tilde{G}^{A\nu}_\mu G^{B\lambda}_\nu G^{C\mu}_\lambda \qquad \mathcal{O}_{\varphi u} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}\gamma^\mu u)$$

$$\mathcal{O}_{qd}^{(8)} = (\bar{Q}\gamma_\mu T^A Q)(\bar{d}\gamma^\mu T^A d) \qquad \mathcal{O}_{\varphi G} = (\varphi^\dagger\varphi)G^A_{\mu\nu}G^{A\mu\nu} \qquad \mathcal{O}_{\varphi\tilde{G}} = (\varphi^\dagger\varphi)\tilde{G}^A_{\mu\nu}G^{A\mu\nu}$$

$$\mathcal{O}_{ud}^{(8)} = (\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)\,.$$

$\boxed{234}$ measurements comprising

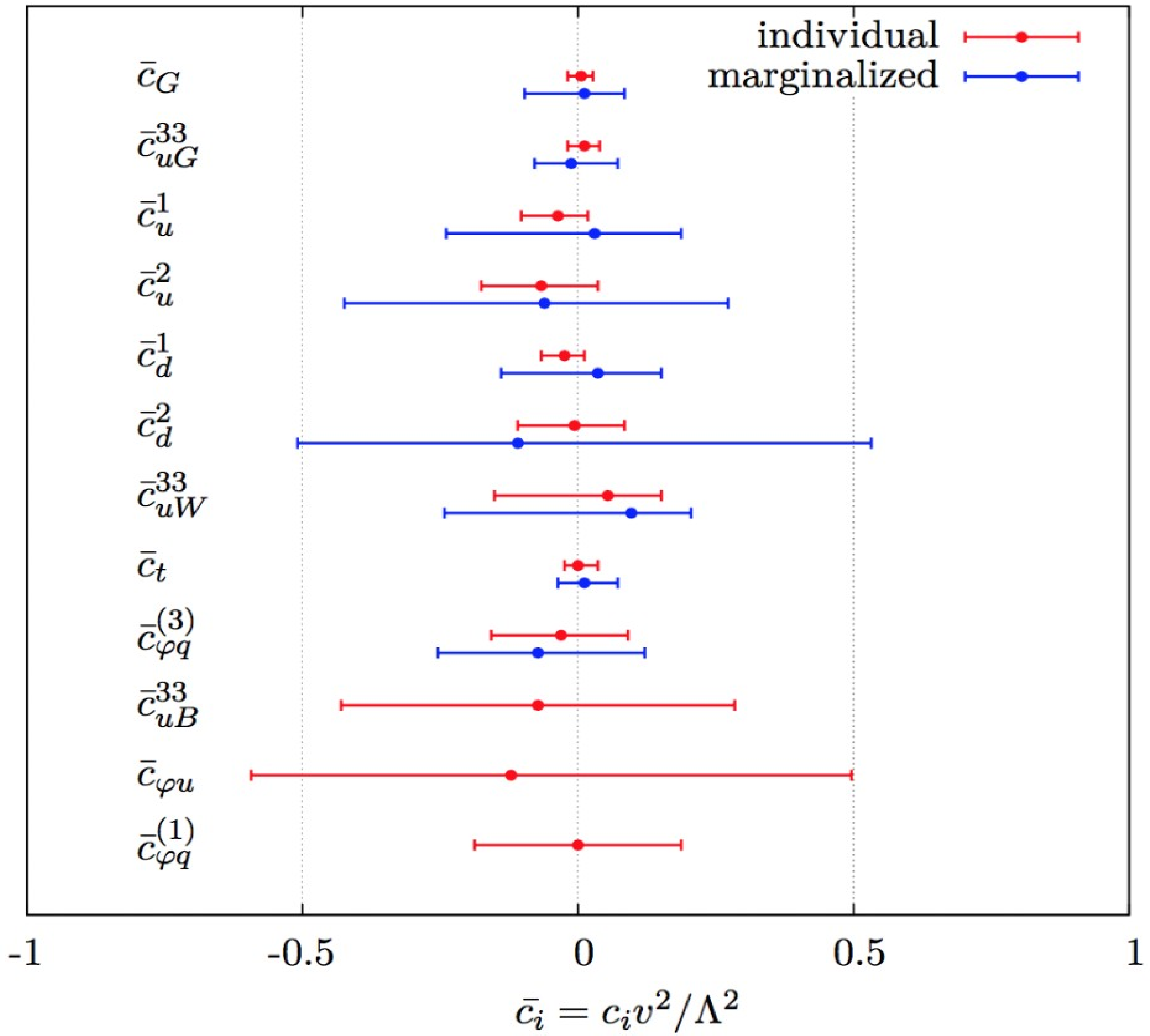
- top pair
- single top (t-channel + s-channel)
- forward backward + charge asymmetries
- associated production (tt+V)
- helicity fractions, top widths
- (total rates+ differential distributions)

Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.	Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.
Top pair production							
Total cross-sections:				Differential cross-sections:			
ATLAS	7	lepton+jets	1406.5375	ATLAS	7	$p_T(t), m_{t\bar{t}}, \lvert y_{t\bar{t}}\rvert$	1407.0371
ATLAS	7	dilepton	1202.4892	CDF	1.96	$m_{t\bar{t}}$	0903.2850
ATLAS	7	lepton+tau	1205.3067	CMS	7	$p_T(t), m_{t\bar{t}}, y_t, y_{t\bar{t}}$	1211.2220
ATLAS	7	lepton w/o b jets	1201.1889	CMS	8	$p_T(t), m_{t\bar{t}}, y_t, y_{t\bar{t}}$	1505.04480
ATLAS	7	lepton w/ b jets	1406.5375	DØ	1.96	$m_{t\bar{t}}, p_T(t), \lvert y_t\rvert$	1401.5785
ATLAS	7	tau+jets	1211.7205				
ATLAS	7	$t\bar{t}, Z\gamma, WW$	1407.0573	Charge asymmetries:			
ATLAS	8	dilepton	1202.4892	ATLAS	7	A_C (inclusive+$m_{t\bar{t}}, y_{t\bar{t}}$)	1311.6742
CMS	7	all hadronic	1302.0508	CMS	7	A_C (inclusive+$m_{t\bar{t}}, y_{t\bar{t}}$)	1402.3803
CMS	7	dilepton	1208.2761	CDF	1.96	A_{FB} (inclusive+$m_{t\bar{t}}, y_{t\bar{t}}$)	1211.1003
CMS	7	lepton+jets	1212.6682	DØ	1.96	A_{FB} (inclusive+$m_{t\bar{t}}, y_{t\bar{t}}$)	1405.0421
CMS	7	lepton+tau	1203.6810				
CMS	7	tau+jets	1301.5755	Top widths:			
CMS	8	dilepton	1312.7582	DØ	1.96	$\Gamma_{\rm top}$	1308.4050
CDF + DØ	1.96	Combined world average	1309.7570	CDF	1.96	$\Gamma_{\rm top}$	1201.4156
Single top production				W-boson helicity fractions:			
ATLAS	7	t-channel (differential)	1406.7844	ATLAS	7		1205.2484
CDF	1.96	s-channel (total)	1402.0484	CDF	1.96		1211.4523
CMS	7	t-channel (total)	1406.7844	CMS	7		1308.3879
CMS	8	t-channel (total)	1406.7844	DØ	1.96		1011.6549
DØ	1.96	s-channel (total)	0907.4259				
DØ	1.96	t-channel (total)	1105.2788				
Associated production				*Run II data*			
ATLAS	7	$t\bar{t}\gamma$	1502.00586	CMS	13	$t\bar{t}$ (dilepton)	1510.05302
ATLAS	8	$t\bar{t}Z$	1509.05276				
CMS	8	$t\bar{t}Z$	1406.7830				

LHC global fit

The first fit that incorporates nearly all Tevatron + LHC data

Not truly global: CP violating observables are ignored, eett operators are not present

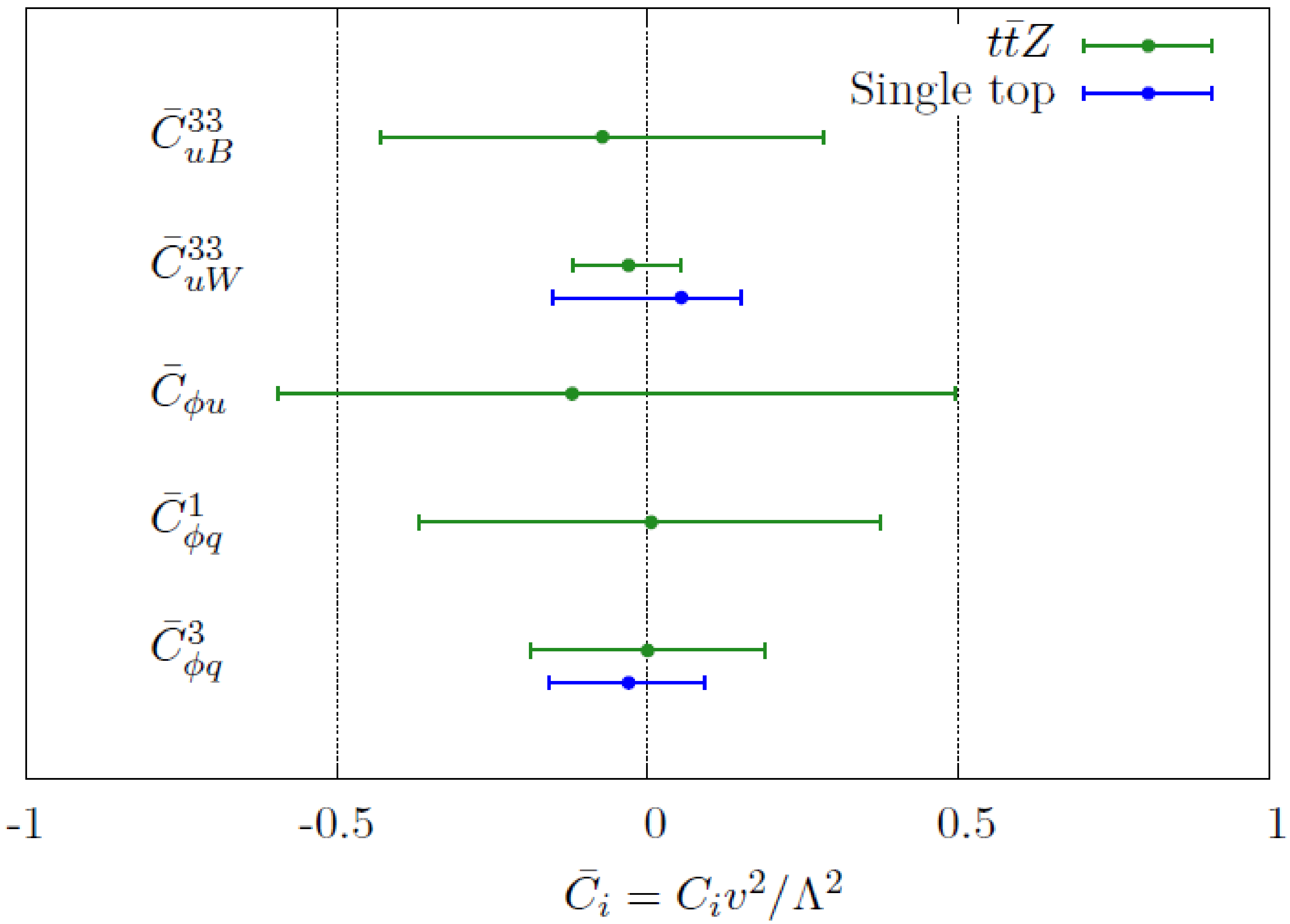


EW top couplings at the LHC

Simultaneous fit to Tevatron and LHC data
arXiv:1506.08845, arXiv:1512.03360

Electro-weak couplings constrained by top decay, single top production, associated ttZ and ttγ production

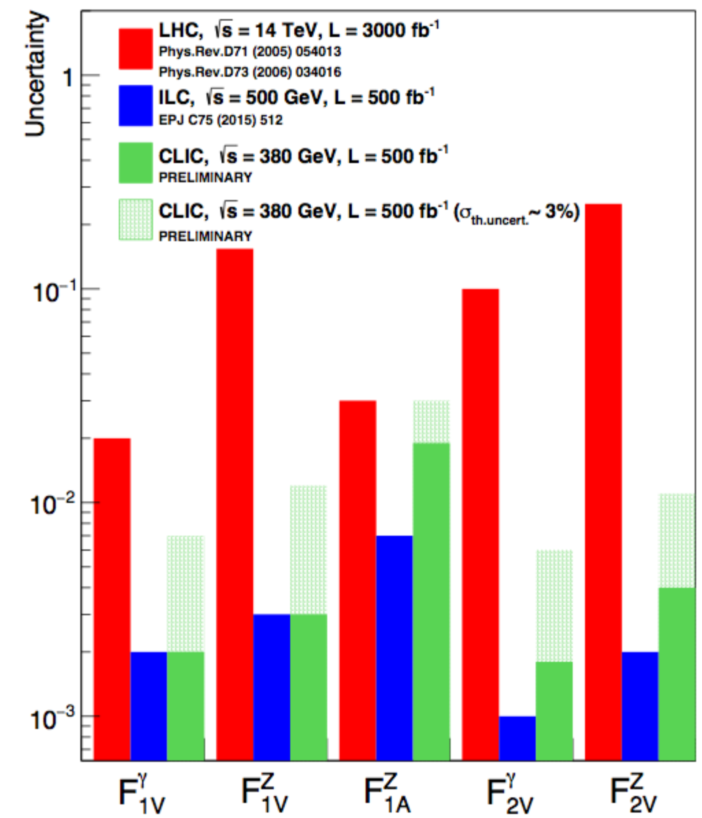
Very weak limits so far!!



See also: M. Perelló, M. Vos, arXiv:1512.07542

Top quark EW couplings at the LC

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



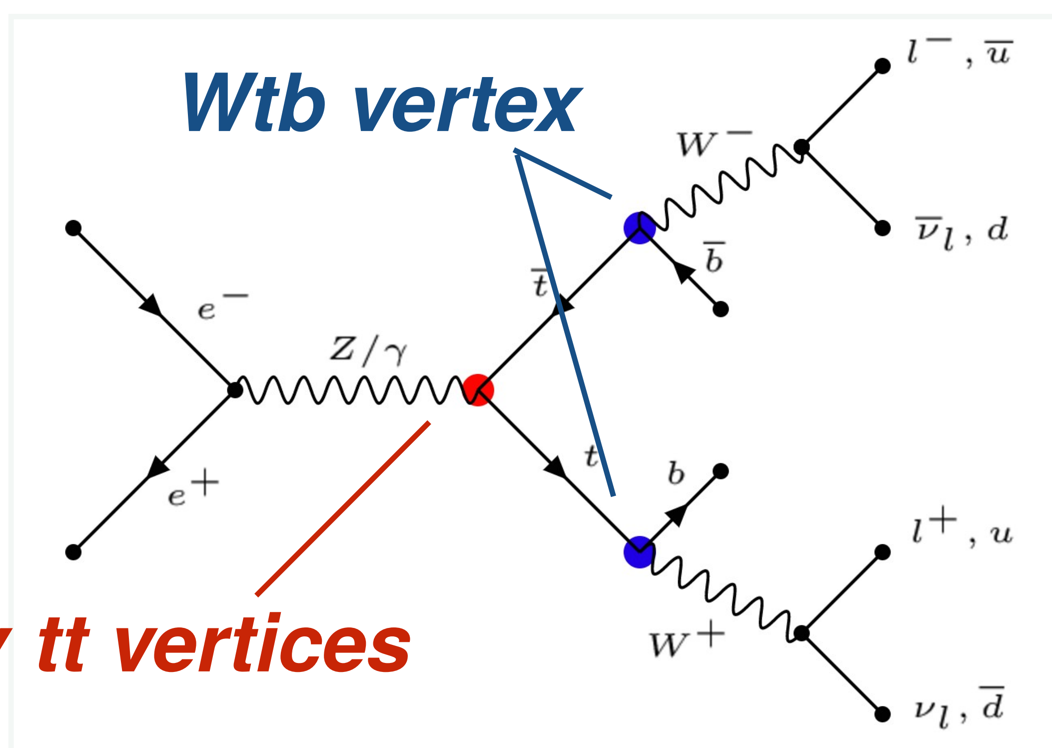
<u>Form-factors</u>

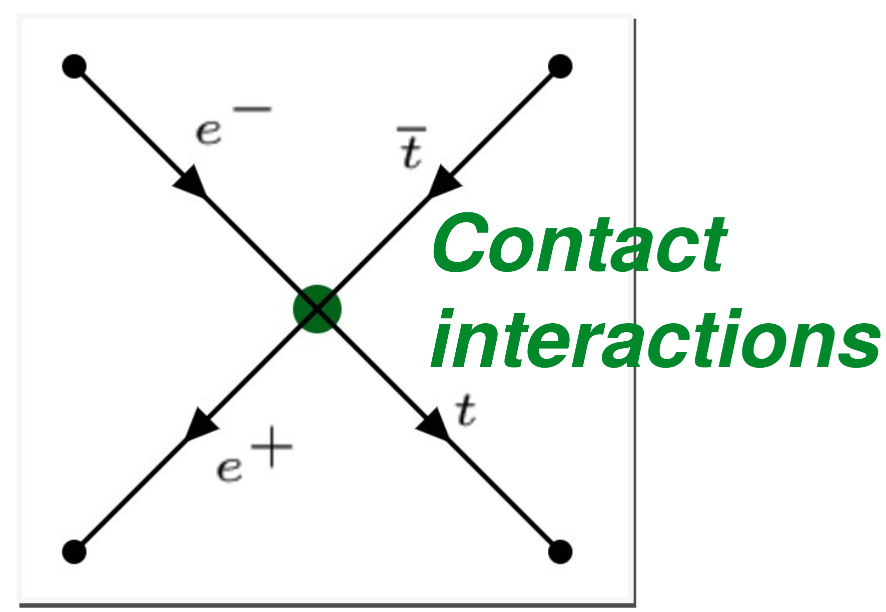
$$\Gamma_\mu^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2)+\gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2)+\gamma_5 F_{2A}^X(k^2)\right)\right\}$$

CP Conserving **CPV**

<u>Effective Field Theory</u>

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

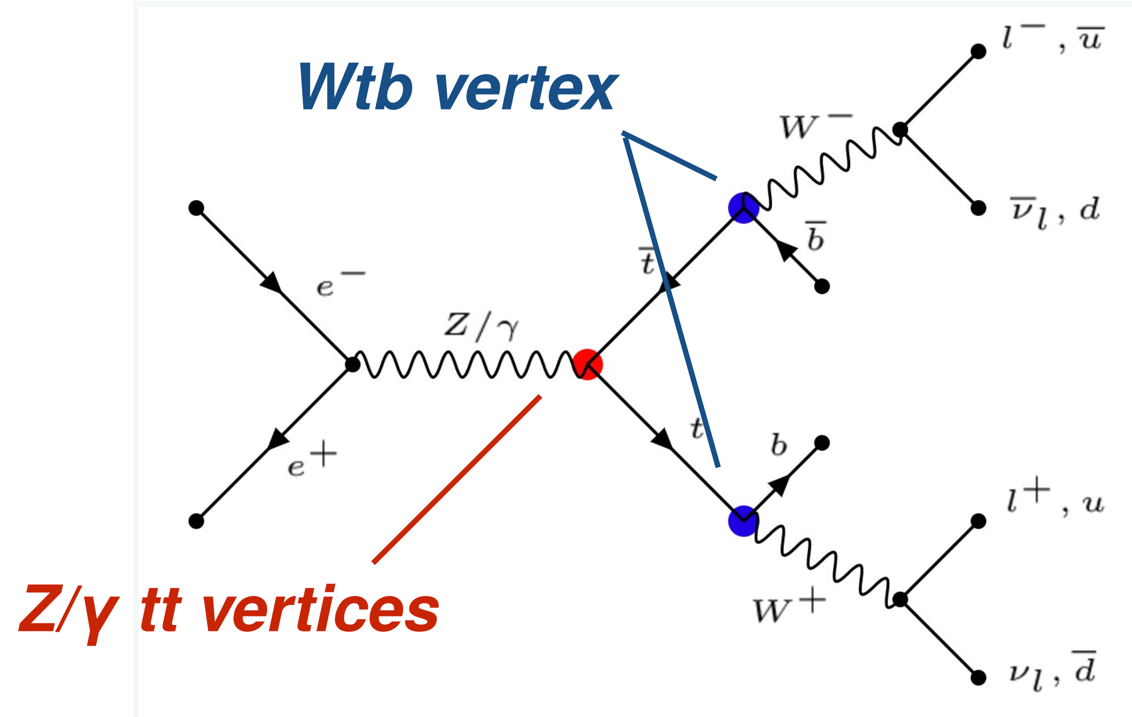




Dim-6 operators

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

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

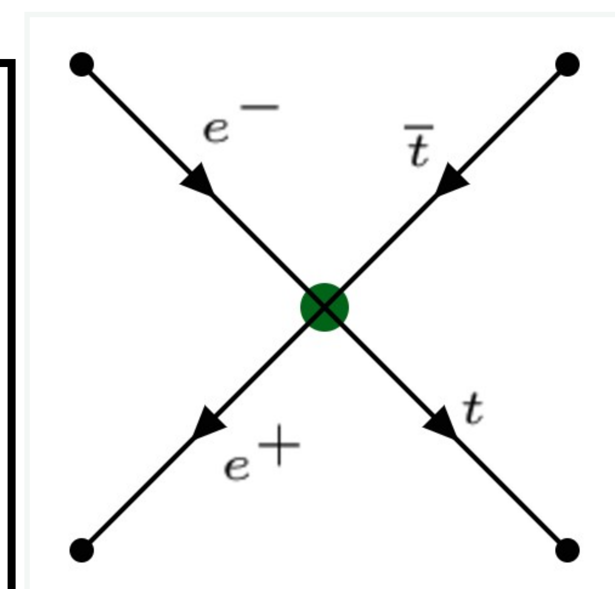


Contact interactions

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

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

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



Form factors ↔ Wilson coefficients

Transformation between effective operators and form-factors:

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

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

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

CP violation

CP violation in top quark pair production

CP violating couplings

The F2A form factors of the general Lagrangian violate the combined CP-symmetry

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

There are two complex form factors, F_{2A}^{γ} and F_{2A}^{Z}. Their real part maps onto the imaginary part of the dipole moment operators C_{tW} and C_{tB}, the imaginary, absorptive part of F2A has no equivalent in FTE

TESLA TDR: CP violationg (F2A) form factors can be precisely extracted.

Optimal observables proposed by Bernreuther et al:

$$O_+^{Re} = (\hat{q}_+^* \times \hat{q}_{\bar{X}}) \cdot \hat{e}_+$$

$$O_+^{Im} = -[1+(\frac{\sqrt{s}}{2m_t}-1)(\hat{q}_{\bar{X}}\cdot\hat{e}_+)^2]\hat{q}_+^*\cdot\hat{q}_{\bar{X}} + \frac{\sqrt{s}}{2m_t}\hat{q}_{\bar{X}}\cdot\hat{e}_+\hat{q}_+^*\cdot\hat{e}_+$$

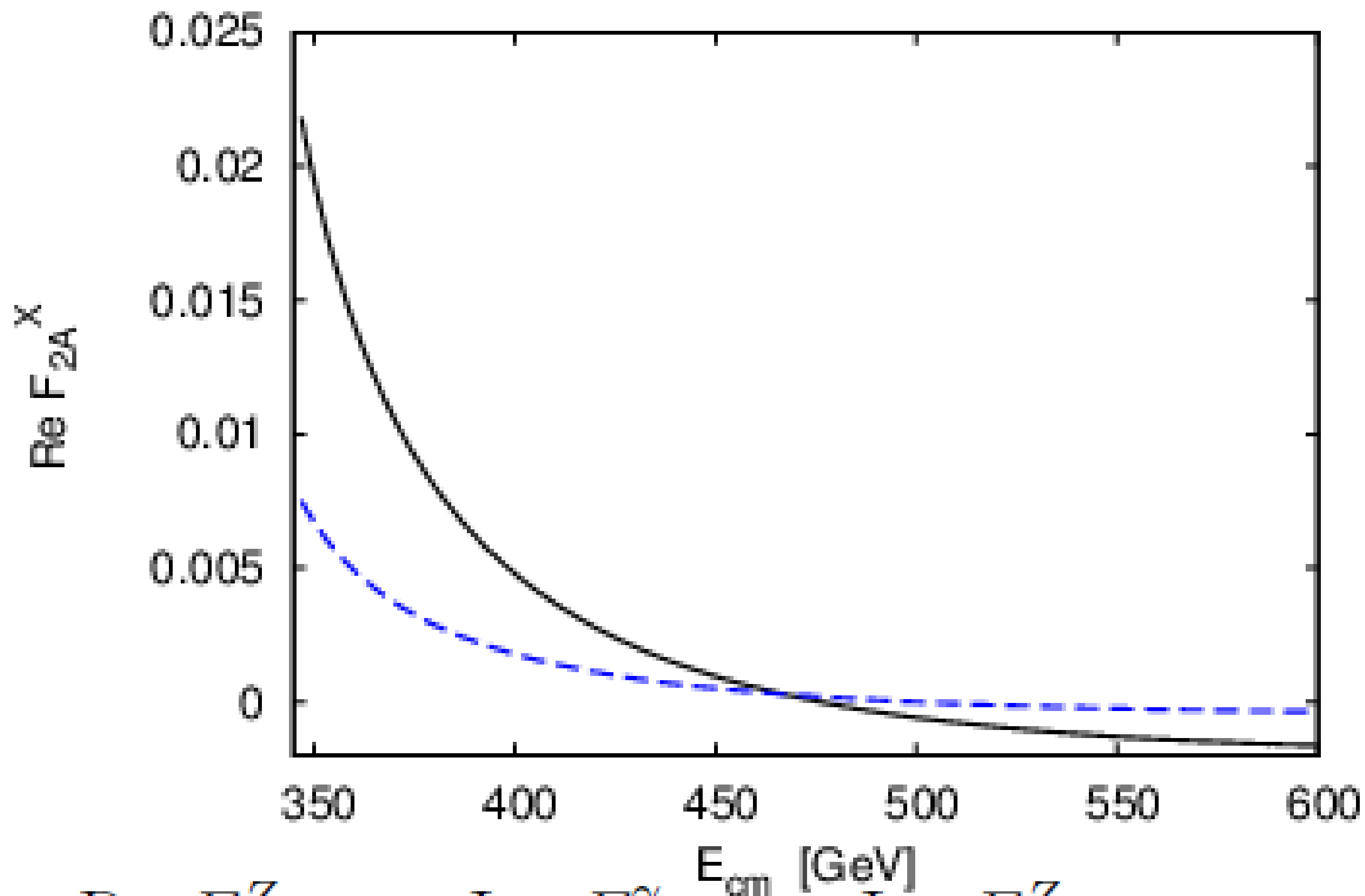
CP violating couplings

Question: how large can CP-violating deviations from SM couplings be?

Empirically, they can be nearly any size. Most global analyses of Tevatron/LHC data ignore CP-violating operators. Study of the tWb vertex provides weak, indirect limits. Low energy analyses pose rather strict, but very indirect limits.

In a motivated model, the effect tends to be quite subtle. The maximum allowed value for F2A is order 0.01 in a 2HDM model that respects all experimental constraints of the Higgs sector

W. Bernreuther, L. Chen (RWTH Aachen)
Up-to-date maximum values for F2A
To be published with LAL-IFIC analysis



$\sqrt{s}$ [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}

Experimental study

Sizeable experimental effects in realistic simultion + reconstruction:

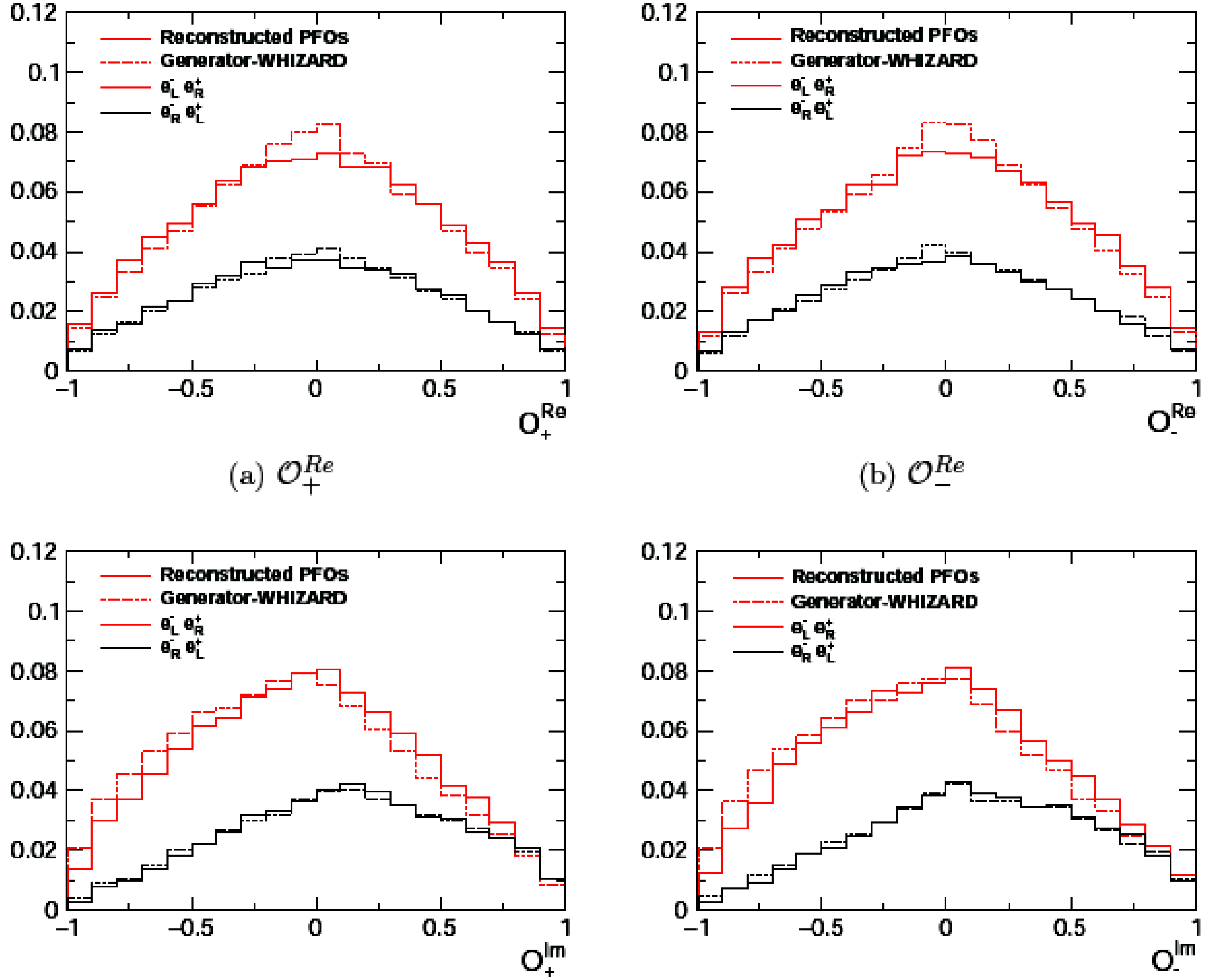
Beam polarization skews O^{Im}

Large acceptance effect and smearing due to ambiguity in bW pairing at low energy

Large acceptance and resolution effects for boosted top quark reconstruction

Nearly all systematic effects cancel in asymmetry

The advantage of measuring “0”. The systematic bias of a null measurement can be controlled at the per-mil level. In case a non-zero value is found the non-linearity can be sizeable....



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

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

Table 4: The main systematics evaluated for the asymmetry $\mathcal{A}^{Re}$ for left-handed polarized electron beam (and right-handed positron beam in the case of 500 GeV operation).

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)	$\pm$ 5%	$\pm$ 2%	-

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

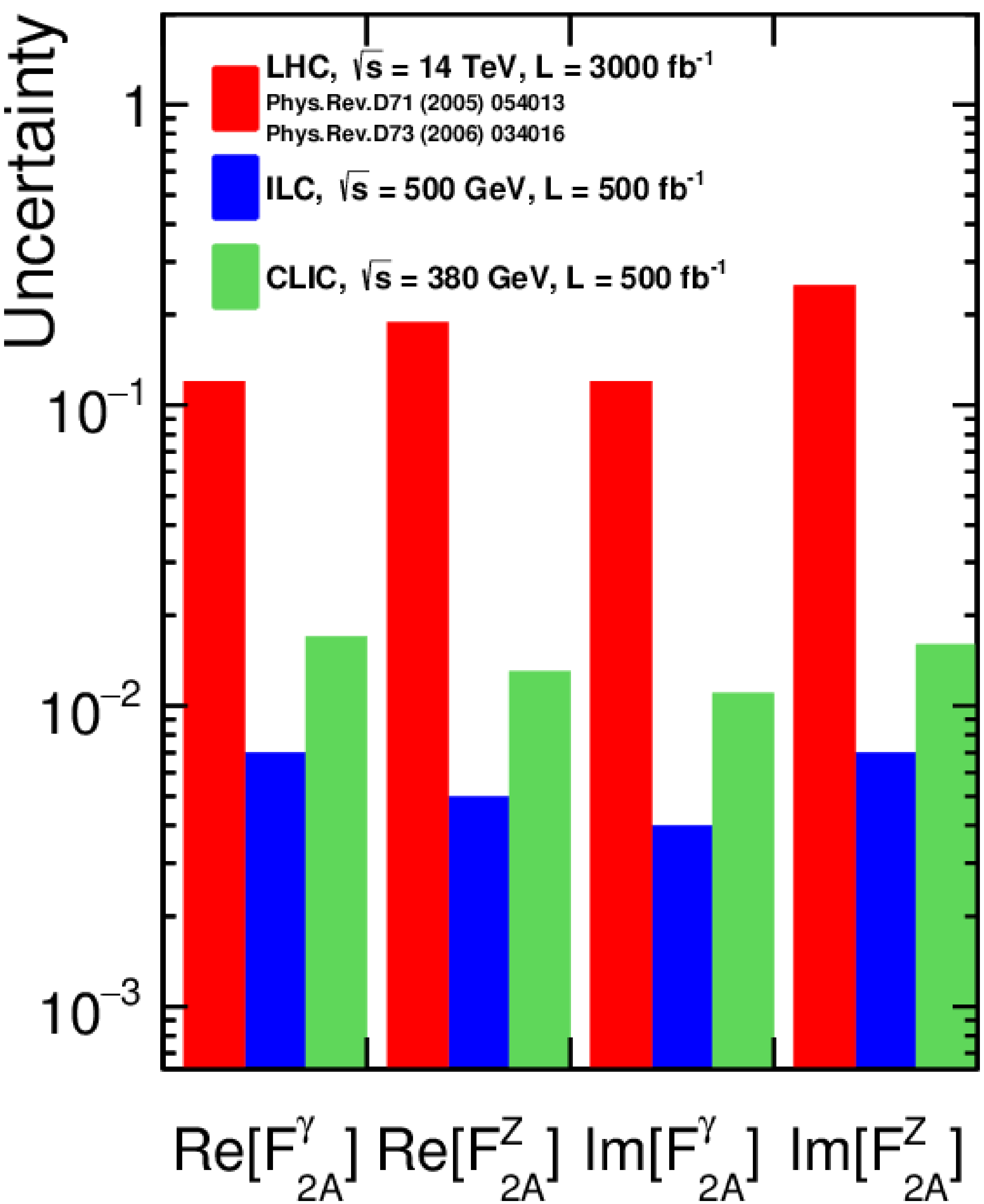
Comparison of potential

ILC results have improved somewhat after a rigorous evaluation of the relations of F2A and optimal observables by Bernreuther et al.

Still **preliminary** today, but hope to submit the paper in a few weeks

Main comparison with old "Snowmass" studies from 2006 (the only study to present prospects for the complete set of form factors)

A comparison with more recent literature is painful due to differences in convention, but most relevant results are ready

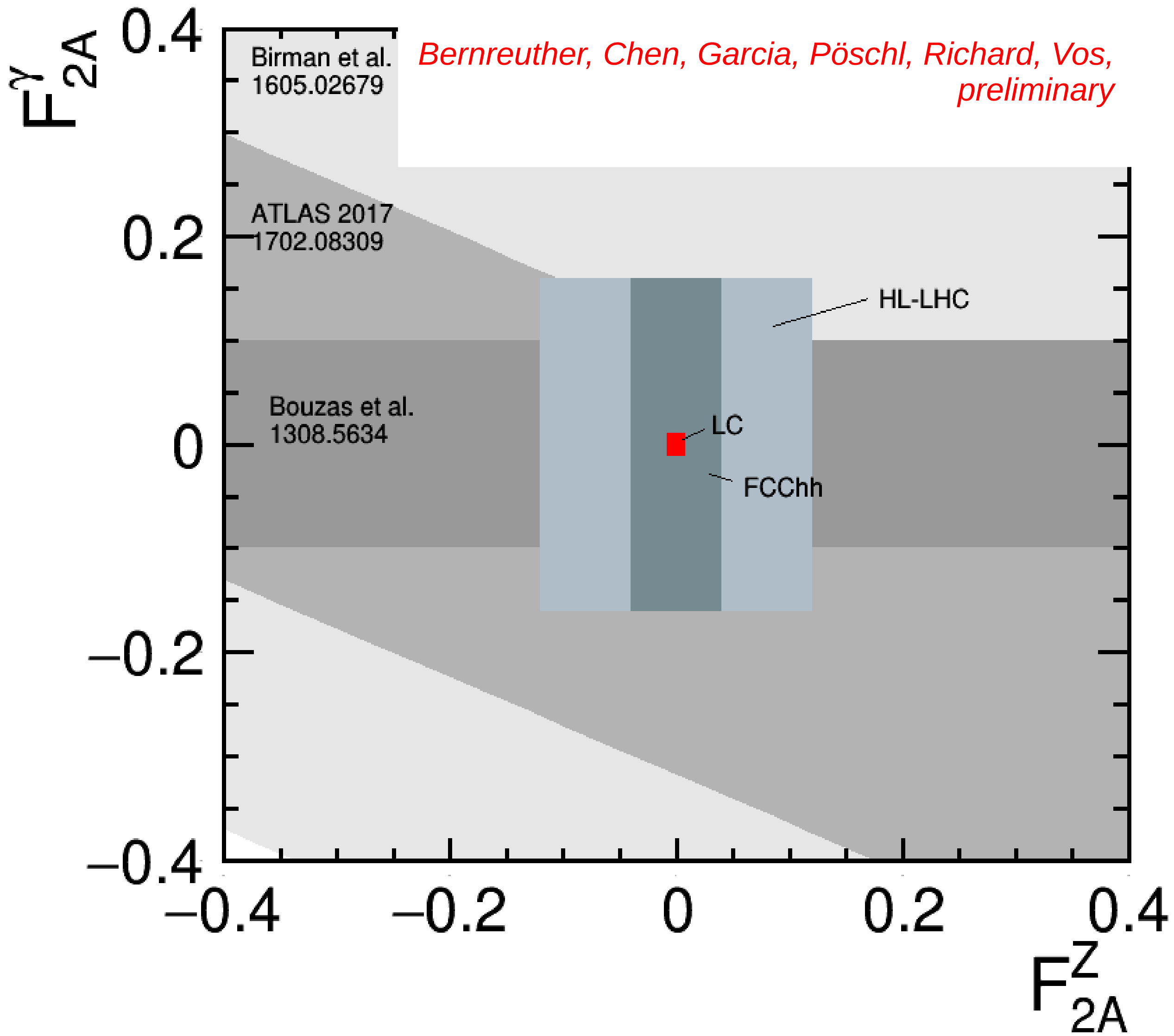


CP-violating couplings: summary

If we do not discover signs of (BSM) CP-violation, the LHC will provide an impressive improvement of the limits on F2A

LHeC can measure F2A of the photon with better precision
FCChh (Schulze et al.) can improve F2AZ further

Best measurement – by far – expected to come from Linear Collider



CPV Publication

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

W. Bernreuther[1], L. Chen[1], I. García [2], M. Perelló[2], R. Poeschl[2], F. Richard[2], E. Ros[2], M. Vos[2]

[1] Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen University, 52056 Aachen, Germany

[2] Instituto de Física Corpuscular (IFIC, UVEG/CSIC), Apartado de Correos 22085, E-46071, Valencia, Spain

[3] Laboratoire de l'Accélérateur Linéaire (LAL), Centre Scientifique d'Orsay, 91898 Orsay Cédex, France

Results are final

Paper is written

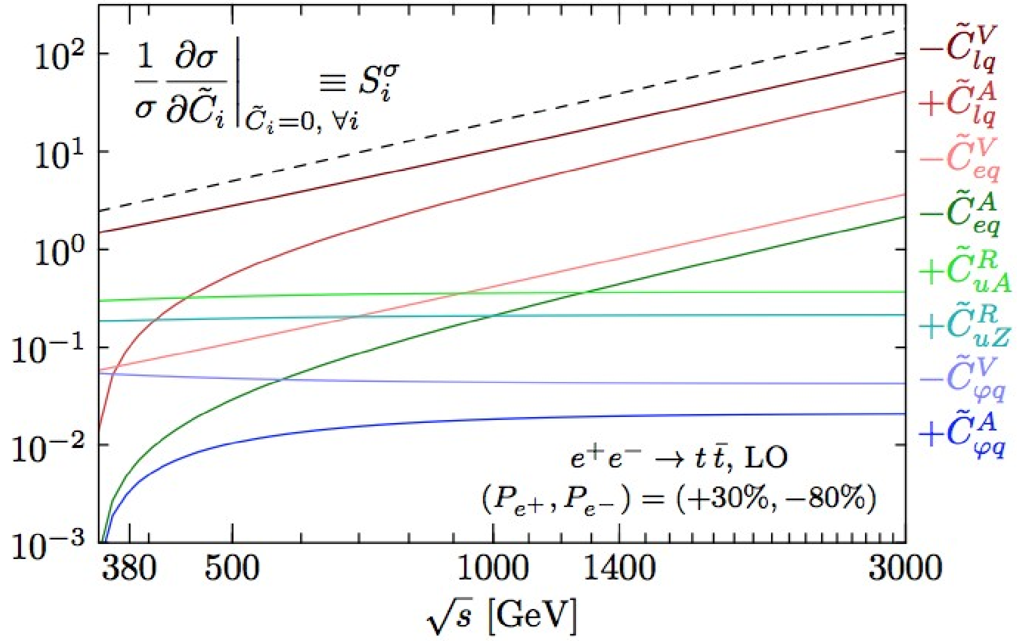
Go for ILD/CLIC circulation as soon as last comments are processed.

Towards a global fit

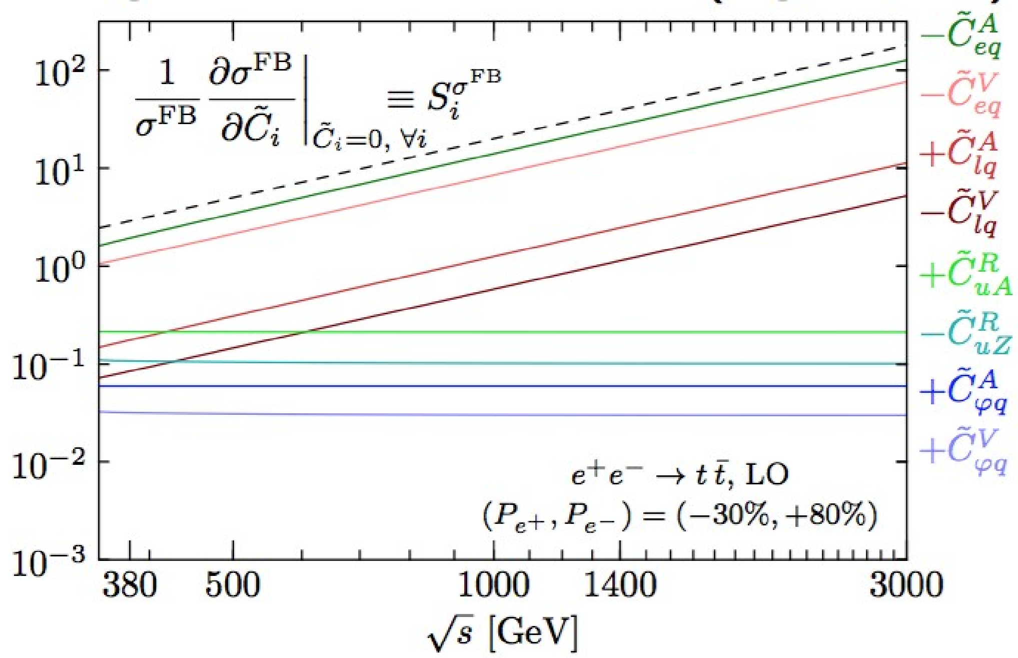
– consider sqrt(s) a free parameter

Observables sensitivity

Total cross section (left pol.):



FB-integrated cross section (right pol.):



Few features:

- quadratic energy growth for four-fermion operators
- no growth for two-fermion operators (dipoles included)
- p-wave $\beta = \sqrt{1 - 4m_t^2/s}$ suppression of axial vectors at threshold
- enhanced sensitivity of axial vector operators in σ^{FB}
- sensitivity sign flip for $C_{\varphi q}^V$ and C_{uZ}^R when polarization is reversed
- etc.

Ideal scenario combines two runs: a high-energy run to constrain 4-fermion operators + a long ~500 GeV run to constrain 2-fermion operators

Dipole operators [Atwood,Soni ’92] [Diehl,Nachtmann ’94]

The flat sensitivity to the magnetic dipole operators C_{tW} and C_{tB} is somewhat puzzling: we naively expected it to grow with center-of-mass energy

Understood: helicity-flip halts growth in most observables. The sensitivity of an optimal observable must indeed grow *Atwood, Soni, PRD45 (1992)*

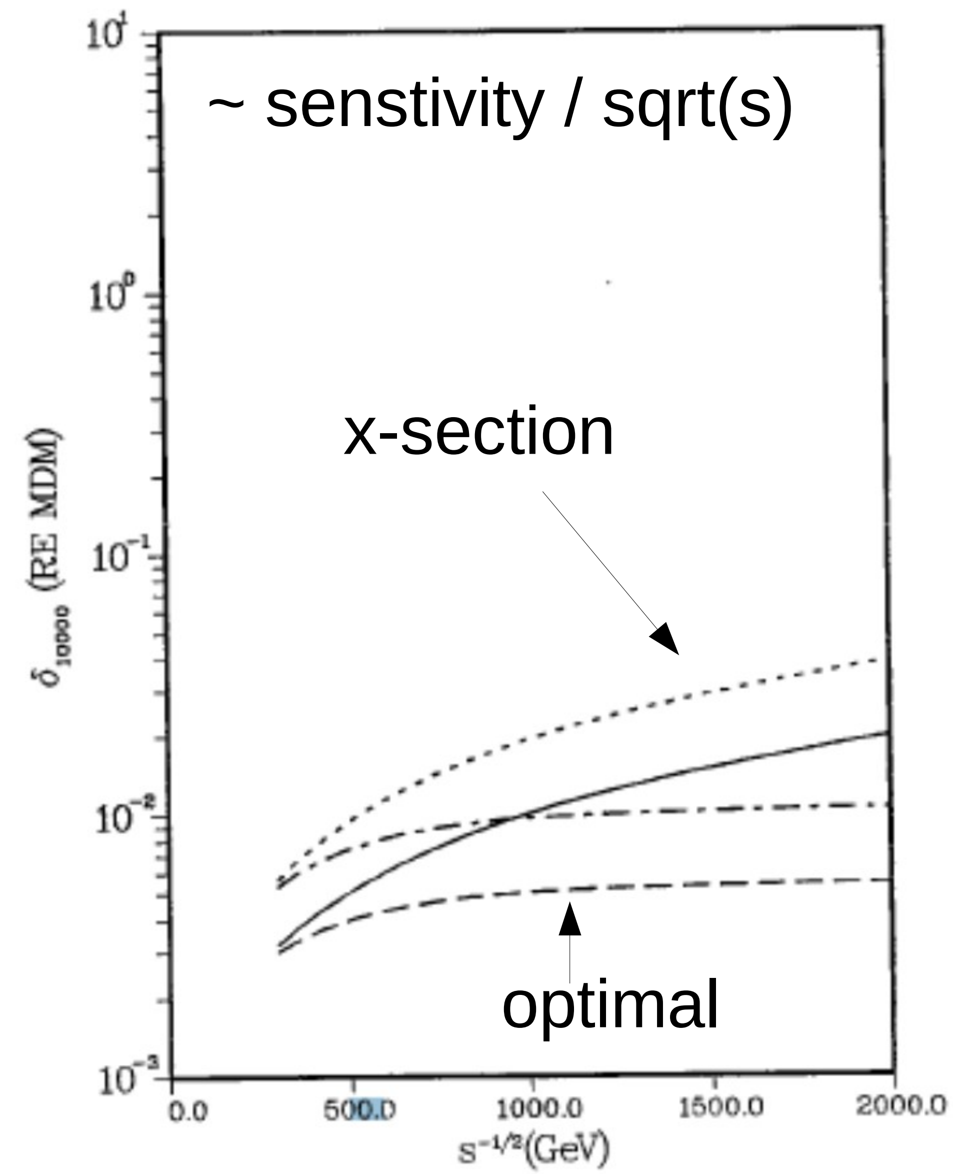
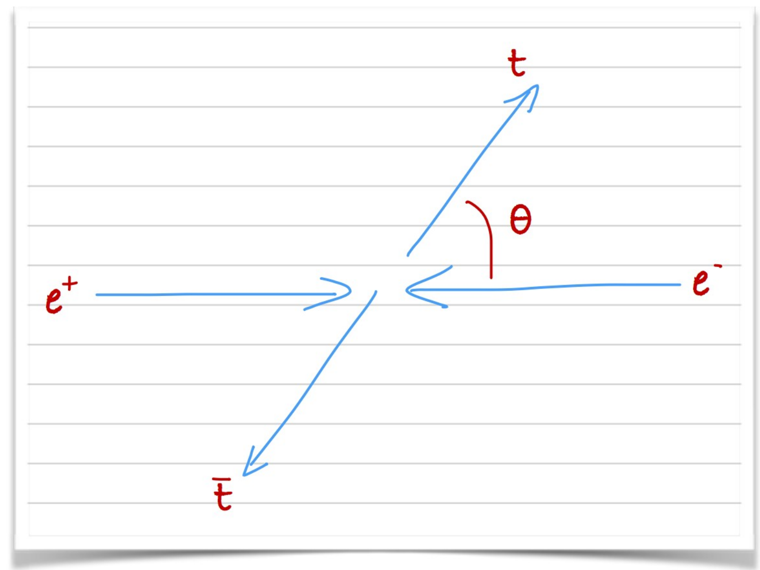


Figure 2b: Right Polarized

Top quark polarization

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

J.A. Aguilar, LC top workshop
Unified approach to polarisation measurements

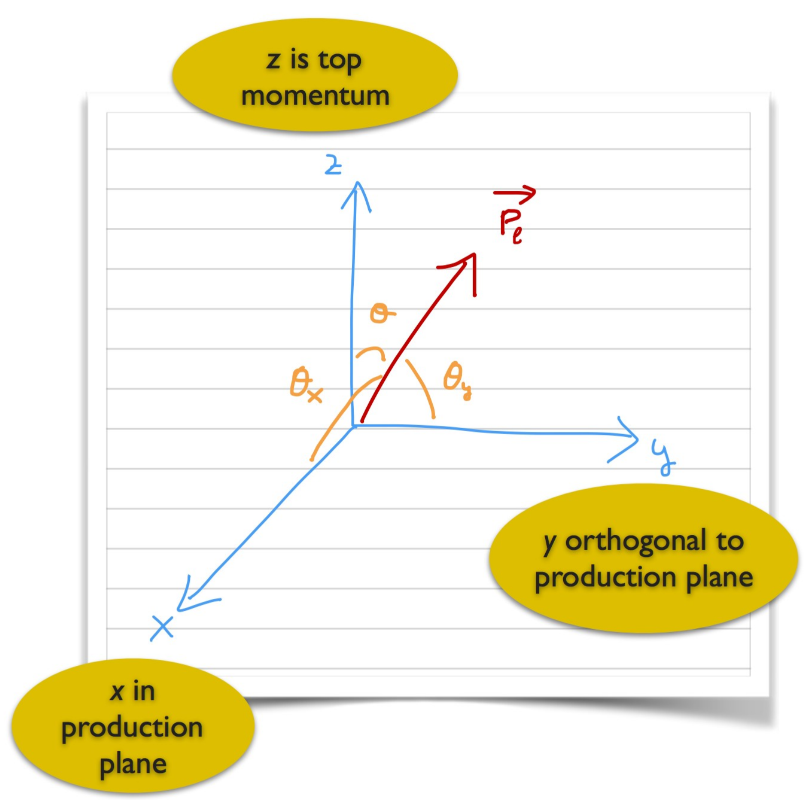


initial state well defined: $e^+ \neq e^-$

$$\hat{z} = \frac{\vec{p}_t}{|\vec{p}_t|}$$

$$\hat{y} = \frac{\vec{p}_t \times \vec{p}_{e+}}{|\vec{p}_t \times \vec{p}_{e+}|}$$

$$\hat{x} = \hat{y} \times \hat{z}$$



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

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

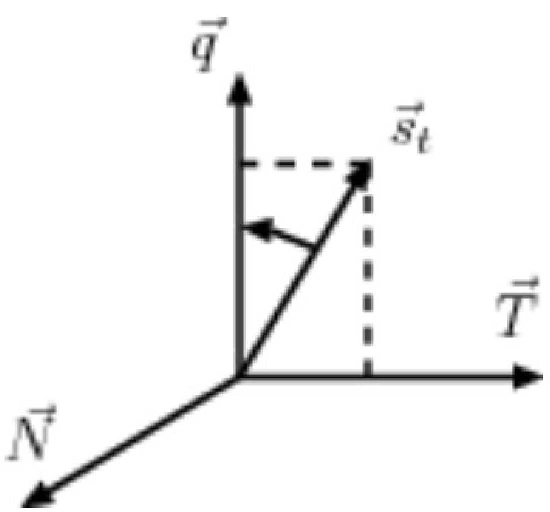
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_y} = \frac{1}{2}(1 + \alpha P_2 \cos\theta_y)$$

Top quark polarization

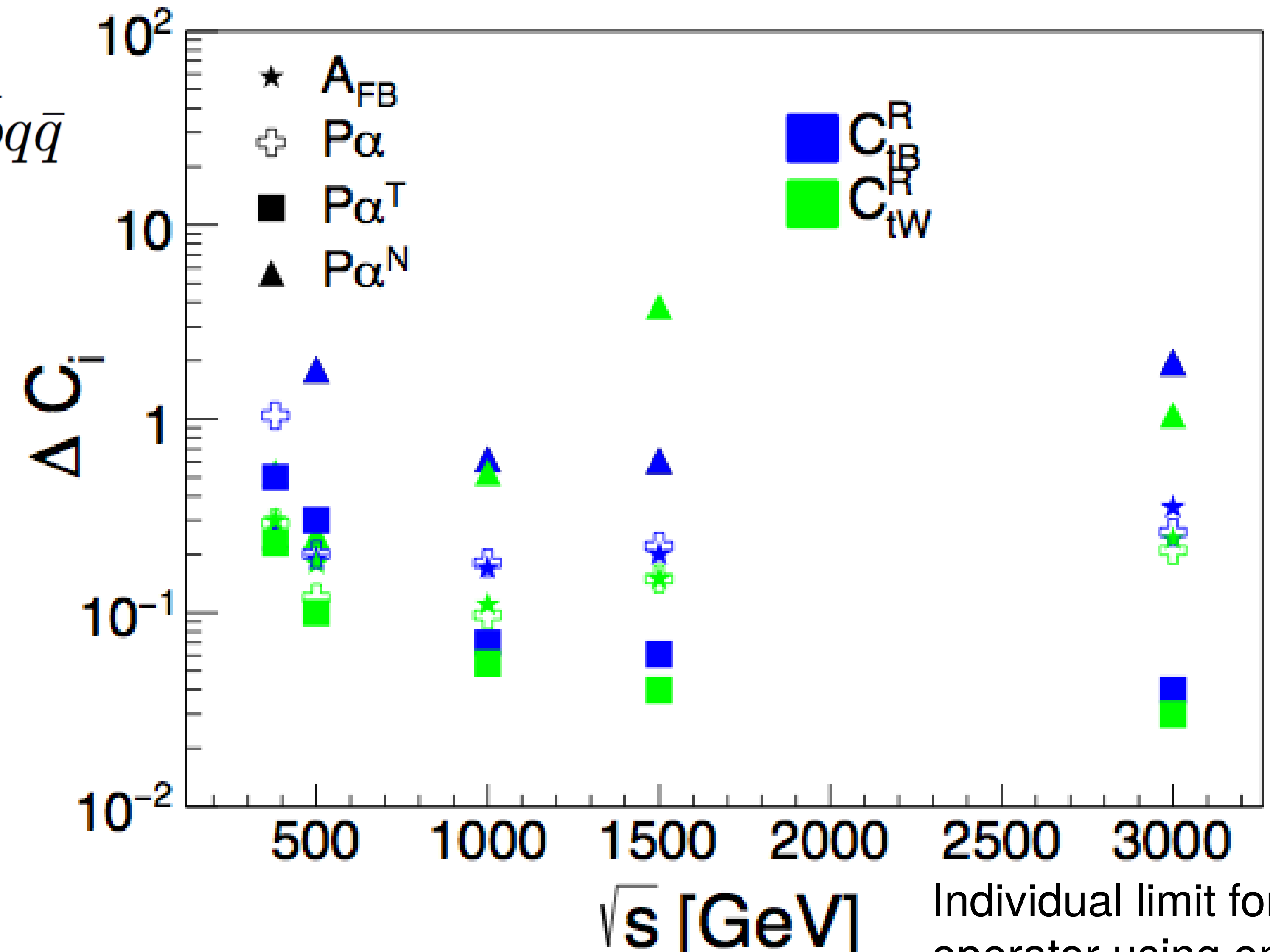
Studied process

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

Defining



$$\vec{N} = \vec{s}_t \times \vec{q}$$
$$\vec{T} = \vec{q} \times \vec{N}.$$



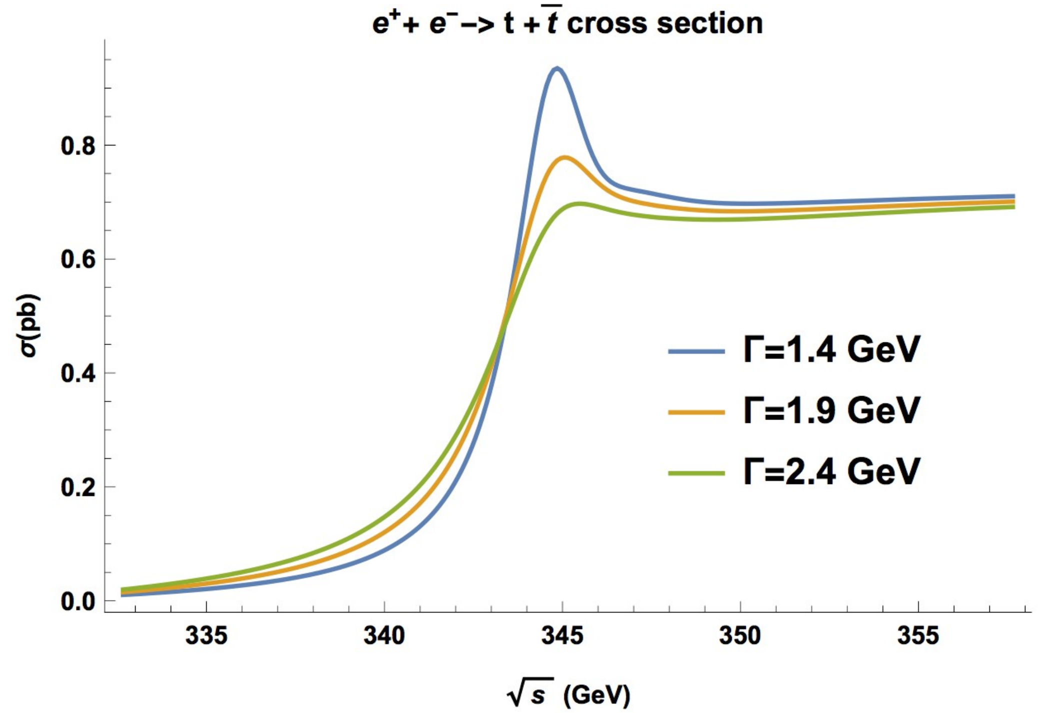
Individual limit for each operator using one observable and energy each time

Transverse axis provide good sensitivity for the **real parts of CtB and CtW**
Sensitivity increases strongly at **high energies**.

Next step: include this observable in the global fit.

Top decay width

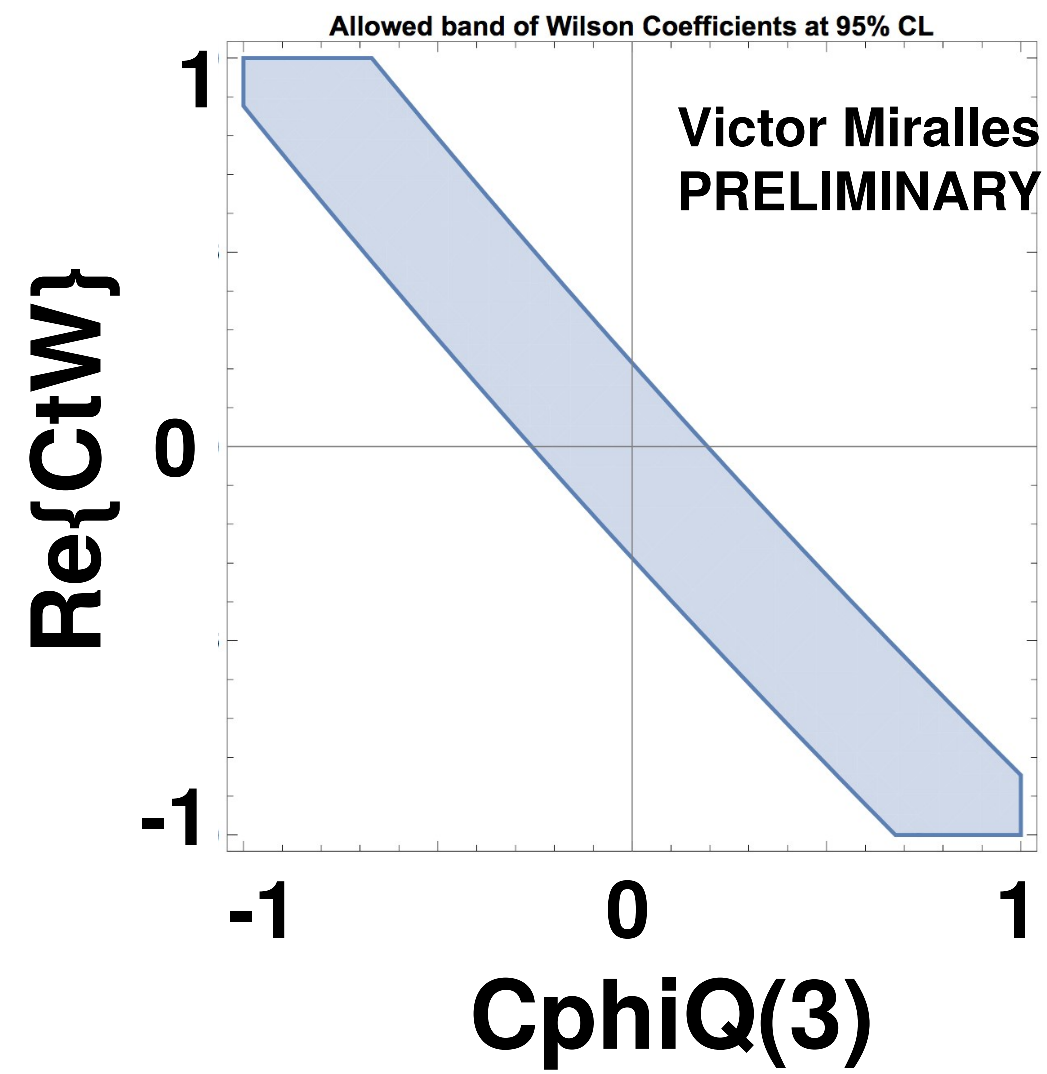
Good measurement at tt~ production threshold



T. Horiguchi, et al. "Study of top quark pair production near threshold at the ILC". arXiv:1310.0563 [hep-ex]. ⇨ **21 MeV stat. uncert.**

V. Miralles at his Master. ⇨ **30 MeV theo. uncert.**

QQbar threshold library @NNNLO



Dependence in **Re{CtW}** and **CphiQ(3)**. Individual limits:

| Re{CtW} | < 0.23 TeV-2
| CphiQ(3) | < 0.21 TeV-2

Synergy bottom-top

For some pairs of operators only a linear combinations can be constrained by top pair production: in particular $c_{\phi q}^{(1)}$ and $c_{\phi q}^{(3)}$

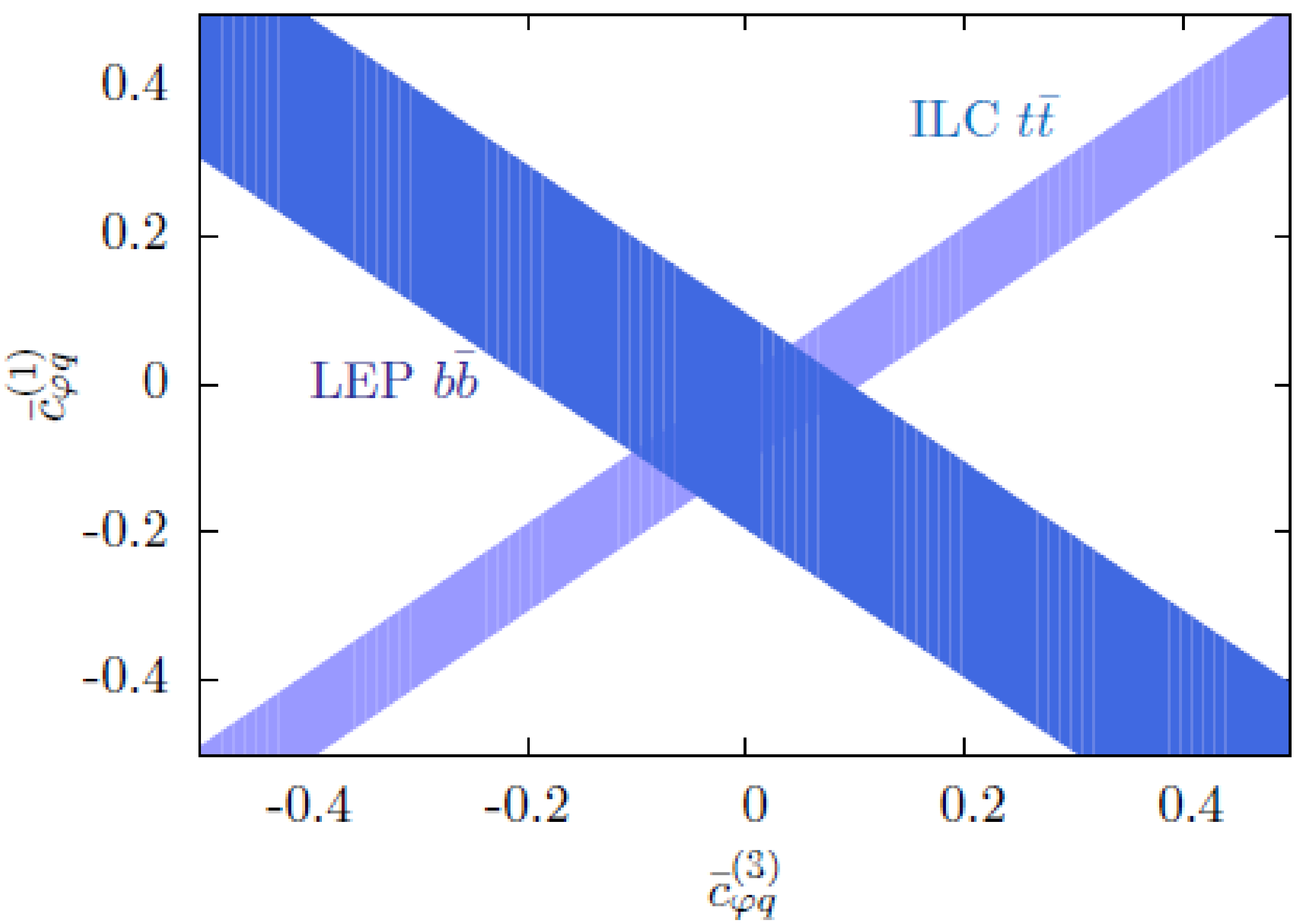
Top quark electroweak couplings at future lepton colliders

Christoph Englert[1,*] and Michael Russell[1,†]

[1]*School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, United Kingdom*

We perform a comparative study of the reach of future e^+e^- collider options for the scale of non-resonant new physics effects in the top quark sector, phrased in the language of higher-dimensional operators. Our focus is on the electroweak top quark pair production process $e^+e^- \to Z^*/\gamma \to t\bar{t}$, and we study benchmark scenarios at the ILC and CLIC. We find that both are able to constrain mass scales up to the few TeV range in the most sensitive cases, improving by orders of magnitude on the forecasted capabilities of the LHC. We discuss the role played by observables such as forward-backward asymmetries, and making use of different beam polarisation settings, and highlight the possibility of lifting a degeneracy in the allowed parameter space by combining top observables with precision Z-pole measurements from LEP1.

ArXiv:1704.01782



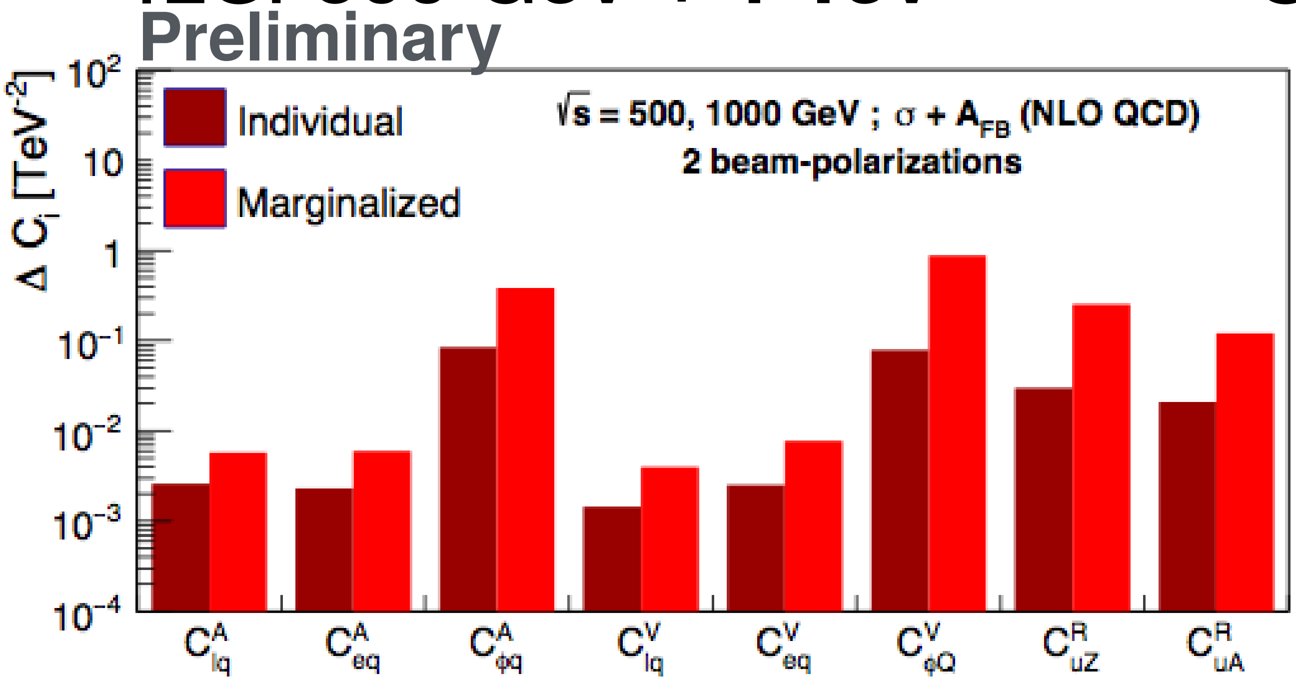
A combined fit of top and bottom allows to constrain those operators

Of course, new constraints, but also new operators...

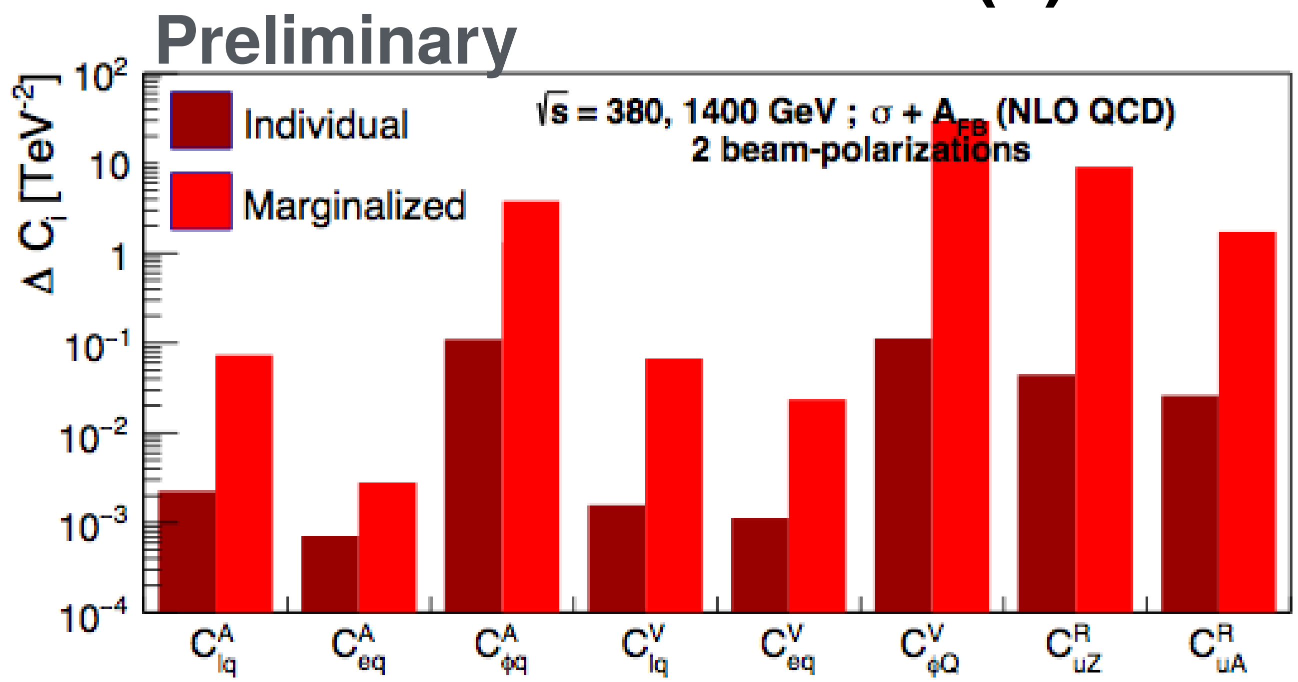
Global Fit: Afb + σ

Studied process $e^-e^+ \to W^+bW^-\bar{b}$ @NLO **[Motivation from arXiv:1411.2355]**

ILC: **500 GeV + 1 TeV**



CLIC: **380 GeV + 1.4 TeV + (3) TeV**



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

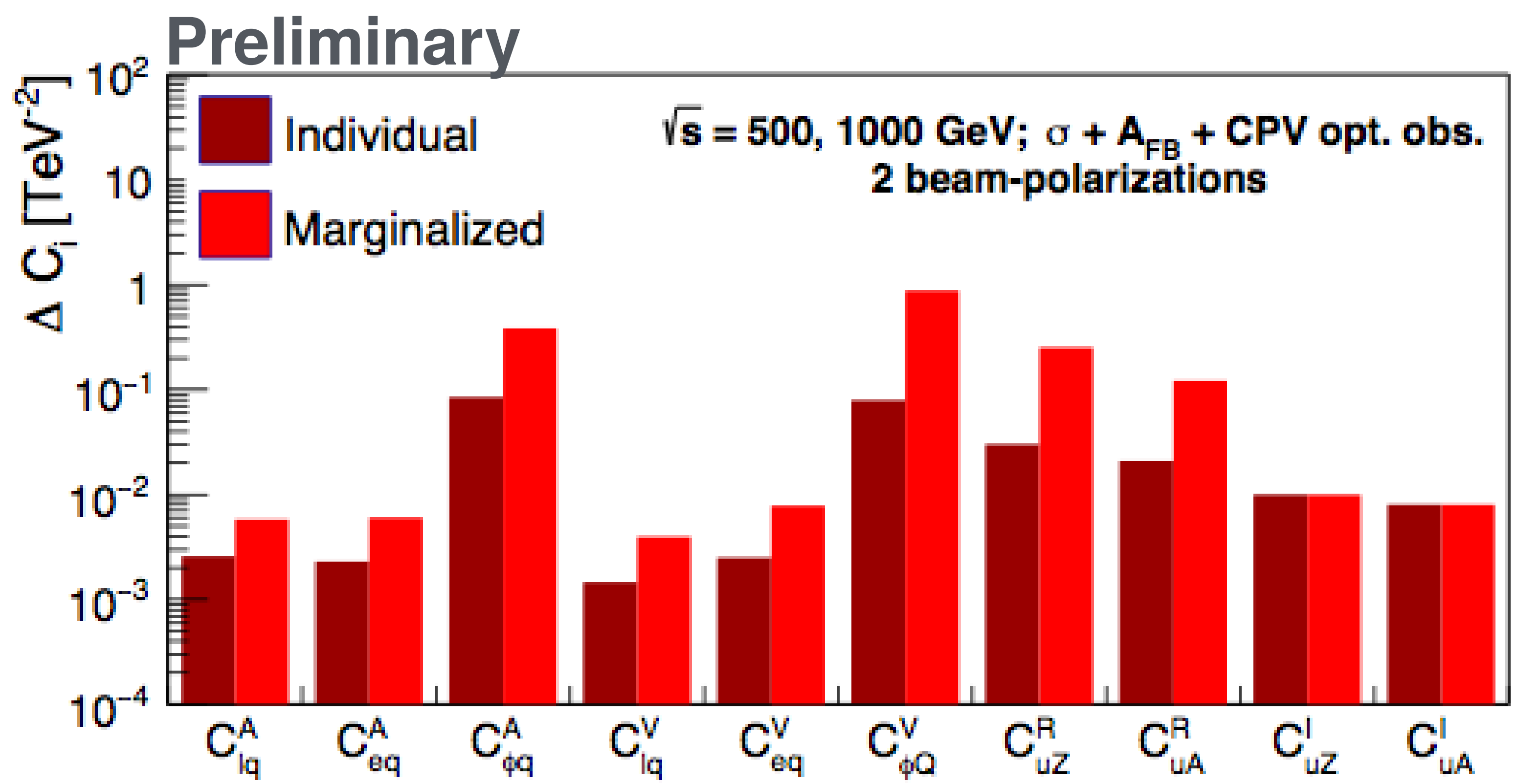
Similar behaviour at $e^-e^+ \to t\bar{t}$ @LO and $e^-e^+ \to W^+bW^-\bar{b}$@NLO (QCD)
Individual limits are very competitive, global constraints much less stringent (marginalized limits >> individual limits)

Need more data to overconstrain the system

Adding CP violation

Including CPV observables in the EFT global fit…

$$\left[F^{Z}_{2,A}, F^{\gamma}_{2,A}\right] \quad \propto \quad \left[\mathrm{Im}\{C_{uA}\}, \mathrm{Im}\{C_{uZ}\}\right]$$



Two additional operators, but also two (x two) new observables

CP conserving and CP violating sectors are “decoupled”

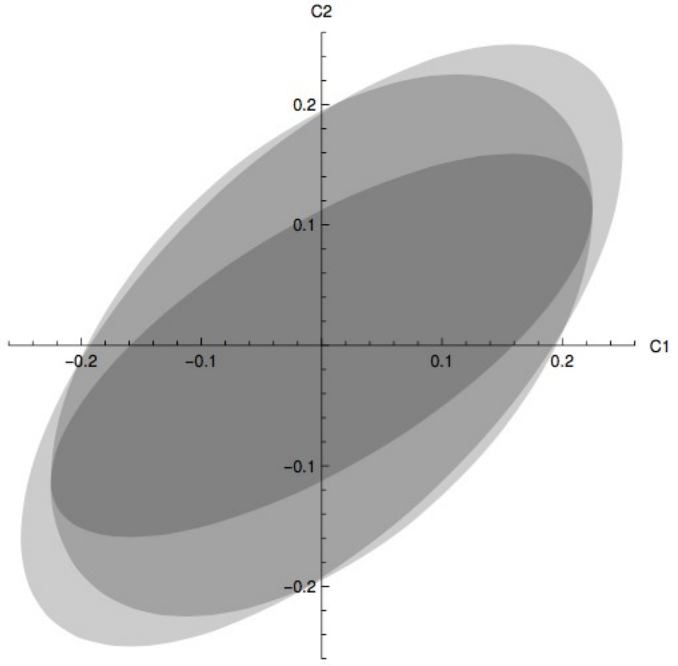
Next steps

Next steps...

Statistically optimal observables

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: $O_i \sim \dfrac{\sin(i\phi)}{1 + \cos\phi}$

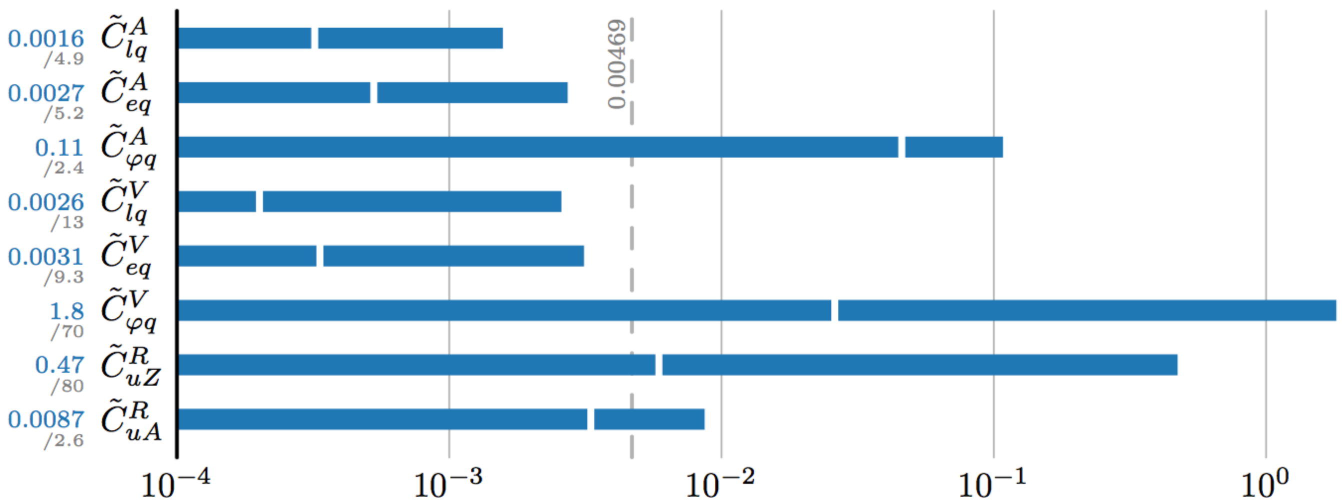
$\Longrightarrow$ area ratios 1.9 : 1.7 : 1

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

Gauthier Durieux: one step ahead

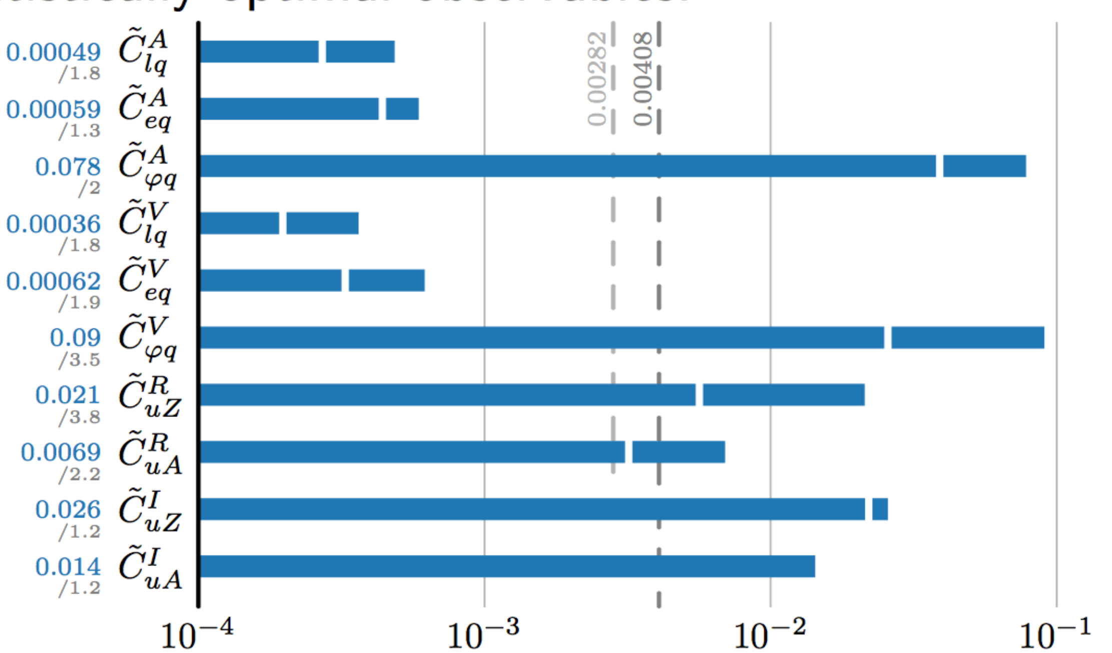
Optimal observables

$\sigma + A^{\mathrm{FB}}$:



Cross section and AFB have good sensitivity. However, with just 2x2 observables the global fit yields poor marginalized limits.

Statistically optimal observables:



Statistically optimal observables can yield much better marginalized results.

Optimal in ideal environment, not very robust in experimental reality? (Yo Sato et al.)

Conclusions

A linear collider running above the top quark pair production threshold can provide more precise constraints on the top quark EW couplings than any other machine (including FCChh/SPPC)

This is particulary true for the CP violating form factors/operators, where an LC is the only machine to reach the sensitivity required in a viable 2HDM

Exploring thepotential of a top physics programme, with multiple center-of-mass energies and measurements of many different observables

Interpret in EFT to facilitate comparison with global top fits