

Top quark flavour-changing neutral currents

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Global approach to top-quark flavor-changing interactions,
GD, F.Maltoni, C.Zhang, Phys.Rev. D91 (2015) 074017, [1412.7166]

Global effective-field-theory interpretation of top-quark FCNCs, GD, T.Kitahara,
C.Zhang, in *Opportunities in Flavour Physics at the HL-LHC and HE-LHC*,
CERN Yellow Report, [1812.07638]

Top-quark FCNC production, in *The CLIC Potential for New Physics*, GD,
CERN Yellow Reports: Monographs (Geneva, 2018), [1812.02093]



Flavour-changing neutral currents

Vanishingly small in the SM

e.g. top decays:

	Br^{SM}	Br^{exp}
$t \rightarrow cg$	$\sim 10^{-11}$	$\lesssim 10^{-4*}$
$t \rightarrow c\gamma$	$\sim 10^{-12}$	$\lesssim 10^{-3*}$
$t \rightarrow cZ$	$\sim 10^{-13}$	$\lesssim 10^{-4}$
$t \rightarrow ch$	$\sim 10^{-14}$	$\lesssim 10^{-3}$

[Eilam et al, 91]

[Mele et al, 98]

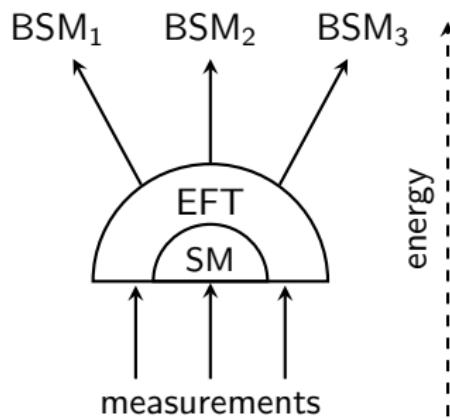
*from production processes

vs. about 10^7 tops produced at the Tevatron and LHC run I
 10^8 from LHC run II at 13 TeV ($1.6 \cdot 10^9/\text{ab}^{-1}$)
 $6 \cdot 10^{10}/\text{ab}^{-1}$ at 100 TeV

The SM EFT

parametrizes systematically the theory space around the SM

- ▶ in a low-energy limit, i.e. for heavy new physics
- ▶ assuming SM fields and encoding its symmetries
- ▶ systematic and consistent when global (RG running, renorm.,...)



LHC TOP WG standards

by the TH community, with extensive feedback from EXP

[1802.07237]

- Fixing normalization and notation,
for convenient linear combination
dedicated:

Interpreting top-quark LHC measurements
in the standard-model effective field theory

[here]

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F. Maltoni,⁴ E. Vryonidou,² C. Zhang⁵ (editors),
D. Barducci,⁶ I. Brivio,⁷ V. Cirigliano,⁸ W. Dekens,^{8,9} J. de Vries,¹⁰ C. Englert,¹¹
M. Fabbrichesi,¹² C. Grojean,^{3,13} U. Haisch,^{2,14} Y. Jiang,⁷ J. Kamenik,^{15,16}
M. Mangano,² D. Marzocca,¹² E. Mereghetti,⁸ K. Mimasu,⁴ L. Moore,⁴ G. Perez,¹⁷
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A. Tonero,²¹ M. Trott,⁷ S. Westhoff,¹⁸ C. White,²² A. Wulzer,^{2,23,24} J. Zupan.²⁵

cutting through reweighting

[Cranmer Heinrich '17]

- Indicative direct & indirect constraints

LHC TOP WG standards

by the TH community, with extensive feedback from EXP

[1802.07237]

- Fixing normalization and notation,
for convenient linear combinations,
dedicated implementation for MC simulation
[here]
- General guiding principle for EFT use,
and conventional assumptions about BSM flavour
to prioritize explorations
- Specific example of global analysis strategy,
identifying useful EXP outputs
See also *Recasting through reweighting*
[Cranmer Heinrich '17]
- Indicative direct & indirect constraints

The up-sector FCNC operators

Two-quark operators:

$$\text{Scalar: } O_{t\varphi} \equiv \bar{q} u \tilde{\varphi} (\varphi^\dagger \varphi - v^2/2),$$

$$\text{Vector: } O_{\varphi q}^+ + O_{\varphi q}^- \equiv \bar{q} \gamma^\mu q \varphi^\dagger \overleftrightarrow{iD}_\mu \varphi,$$

$$O_{\varphi q}^+ - O_{\varphi q}^- \equiv \bar{q} \gamma^\mu \tau^I q \varphi^\dagger \overleftrightarrow{iD}_\mu^I \varphi,$$

$$O_{\varphi u} \equiv \bar{u} \gamma^\mu u \varphi^\dagger \overleftrightarrow{iD}_\mu \varphi,$$

$$\text{Tensor: } c_W O_{uA} - s_W O_{uZ} \equiv \bar{q} \sigma^{\mu\nu} u \tilde{\varphi} B_{\mu\nu},$$

$$s_W O_{uA} + c_W O_{uZ} \equiv \bar{q} \sigma^{\mu\nu} \tau^I u \tilde{\varphi} W_{\mu\nu}^I,$$

$$O_{uG} \equiv \bar{q} \sigma^{\mu\nu} T^A u \tilde{\varphi} G_{\mu\nu}^A.$$

Two-quark–two-lepton operators:

$$\text{Scalar: } O_{lequ}^S \equiv \bar{l} e \varepsilon \bar{q} u,$$

$$\text{Vector: } O_{lq}^+ + O_{lq}^- \equiv \bar{l} \gamma_\mu l \bar{q} \gamma^\mu q,$$

$$O_{lq}^+ - O_{lq}^- \equiv \bar{l} \gamma_\mu \tau^I l \bar{q} \gamma^\mu \tau^I q,$$

$$O_{lu} \equiv \bar{l} \gamma_\mu l \bar{u} \gamma^\mu u,$$

$$O_{eq} \equiv \bar{e} \gamma^\mu e \bar{q} \gamma_\mu q,$$

$$O_{eu} \equiv \bar{e} \gamma_\mu e \bar{u} \gamma^\mu u,$$

$$\text{Tensor: } O_{lequ}^T \equiv \bar{l} \sigma_{\mu\nu} e \varepsilon \bar{q} \sigma^{\mu\nu} u.$$

Four-quark operators: ...

$$\overleftrightarrow{D}_\mu^{(I)} \equiv (\tau^I) \overrightarrow{D}_\mu - \overleftarrow{D}_\mu (\tau^I)$$

Independent coefficients for top FCNCs

Two-quark operators: $10 \times 2_{(a=1,2)}$ complex coefficients

Scalar: $c_{t\varphi}^{(a3)}, c_{t\varphi}^{(3a)},$

Vector: $c_{\varphi q}^{+(a+3)},$ (down- Z)
 $c_{\varphi q}^{-(a+3)},$ (up- Z)
 $c_{\varphi u}^{(a+3)},$

Tensor: $c_{uA}^{(a3)}, c_{uA}^{(3a)},$
 $c_{uZ}^{(a3)}, c_{uZ}^{(3a)},$
 $c_{uG}^{(a3)}, c_{uG}^{(3a)}.$

Two-quark–two-lepton operators: $8 \times 2_a \times 2_\ell$ complex coeffs

Scalar: $c_{1equ}^{S(a3)}, c_{1equ}^{S(3a)},$

Vector: $c_{1q}^{+(a+3)},$ (up- ν , down- ℓ)
 $c_{1q}^{-(a+3)},$ (up- ℓ , down- ν)
 $c_{1u}^{(a+3)},$ (up- ℓ , up- ν)
 $c_{eq}^{(a+3)},$ (up- ℓ , down- ℓ)
 $c_{eu}^{(a+3)},$

Tensor: $c_{1equ}^{T(a3)}, c_{1equ}^{T(3a)}.$

Four-quark operators: ...

Anomalous couplings/broken-phase eff. Lagrangian

Schematically:

Scalar: $\bar{t}q h$

Vector: $\bar{t}\gamma^\mu q Z_\mu$

Tensor: $\bar{t}\sigma^{\mu\nu} q A_{\mu\nu}$

$\bar{t}\sigma^{\mu\nu} q Z_{\mu\nu}$

$\bar{t}\sigma^{\mu\nu} T^A q G_{\mu\nu}^A$

Mismatch with EFT:

1. Missing four-point interactions:

- four-fermion operators

- a $tqgh$ vertex arising from
 $\bar{q}\sigma^{\mu\nu} T^A u \tilde{\varphi} G_{\mu\nu}^A$

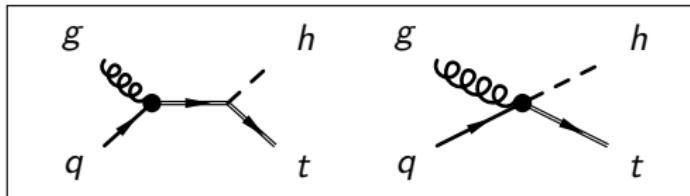
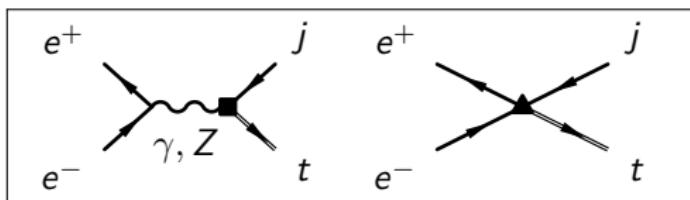
2. Operators of seemingly different dimensions

3. Missed correlations:

- of ' $v + h$ ' type

- of ' $W + Z + \gamma$ ' type

- of ' $(t_L [V_{CKM} d_L]^3)^T$ ' type



Direct searches

	$tqg, tqgh$ T T	$tq\gamma$ T	tqZ V,T	$tq\ell\ell$ S,V,T	$tqqq$ S,V,T	tqh S
The broken-phase effective Lagrangian:	✓ X	✓	✓,✓	X	X	✓
• $e^+e^- \rightarrow t j$ OPAL, DELPHI, ALEPH, L3 $e^- p \rightarrow e^- t$ H1, ZEUS		✓	✓,X	X	X	
production						
• $p \tilde{p} \rightarrow t$ CDF, ATLAS $p \tilde{p} \rightarrow t j$ D0, CMS	✓					
• $p p \rightarrow t \gamma$ CMS $p p \rightarrow t \ell^+\ell^-$ CMS $p p \rightarrow t \gamma\gamma$ —	X	✓	X	X,✓	X	X
	X	X	X			
						2014 status!
decay						
$t \rightarrow j\gamma$ CDF, D0, ATLAS, CMS		✓				
• $t \rightarrow j\ell^+\ell^-$ CDF, D0, ATLAS, CMS		X	✓,X	X		
• $t \rightarrow j\gamma\gamma$ CMS, ATLAS		X				✓

One single contribution is often assumed, although:

- NP could generate several operators at Λ .
- RG mixings would contaminate more of them at E .
- EOM, Fierz identities, etc. have converted some op. into combinations of others.
- Renormalizability requires counterterms from other operators.

➡ A consistent EFT treatment should include *all* operators up to a given dimension!

Interferences and NLO

[1412.7166]

outdated notation!

$$\text{e.g. } \Gamma_{t \rightarrow j \ell^+ \ell^-}^{m_{\ell\ell} \in [78, 102] \text{ GeV}} = 10^{-5} \text{ GeV} \times \left(\frac{1 \text{ TeV}}{\Lambda} \right)^4 \times$$

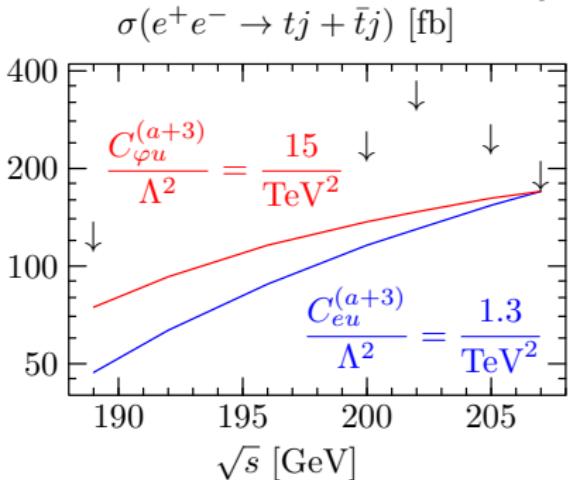
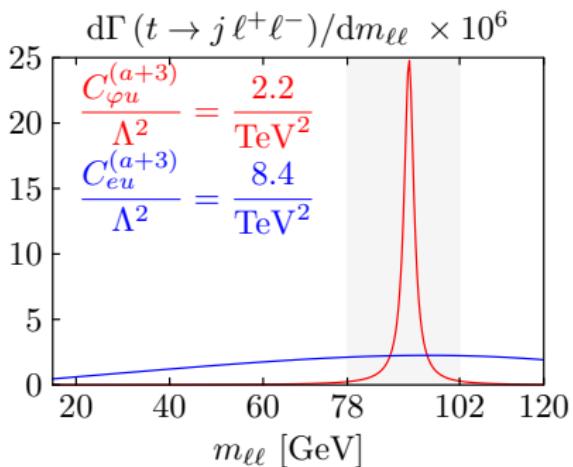
$$\begin{aligned}
& \text{Re} \left(\begin{array}{c} C_{lq}^{-(a+3)} \\ C_{eq}^{(a+3)} \\ C_{\varphi q}^{-(a+3)} \\ C_{uB}^{(a3)} \\ C_{uW}^{(a3)} \\ C_{uG}^{(a3)} \end{array} \right)^\dagger \left(\begin{array}{ccccccc} +0.069 & 0 & -0.02 - 0.2i & -0.053 - 0.1i & -0.052 + 0.34i & +0.014 - 0.013i \\ -9\% & & +6\% -9\% & -5\% -8\% & -16\% -8\% & & \\ & +0.069 & +0.017 + 0.18i & -0.053 + 0.09i & -0.054 - 0.3i & -0.007 + 0.017i & \\ & -9\% & +6\% -9\% & -10\% -8\% & +0\% -8\% & & \\ & & +1.7 & +1.7 - 0.0095i & -5.7 - 0.0095i & +0.27 + 0.2i & \\ & & -9\% & -8\% -8\% & -8\% -8\% & & \\ & & & +0.64 & -3.9 - 0.029i & +0.16 + 0.14i & \\ & & & -9\% & -9\% -9\% & & \\ & & & & +6.6 & -0.53 - 0.47i & \\ & & & & -9\% & & \\ & & & & & +0.002 & \\ & & & & & & C_{uG}^{(a3)} \end{array} \right) \\
& + \text{Re} \left(\begin{array}{c} C_{lu}^{(a+3)} \\ C_{eu}^{(a+3)} \\ C_{\varphi u}^{(a+3)} \\ C_{uB}^{(3a)*} \\ C_{uW}^{(3a)*} \\ C_{uG}^{(3a)*} \end{array} \right)^\dagger \left(\begin{array}{ccccccc} +0.069 & 0 & -0.02 - 0.2i & -0.053 - 0.1i & -0.052 + 0.34i & -0.002 + 0.013i \\ -9\% & & +6\% -9\% & -5\% -8\% & -16\% -8\% & & \\ & +0.069 & +0.017 + 0.18i & -0.053 + 0.09i & -0.054 - 0.3i & +0.0067 - 0.006i & \\ & -9\% & +6\% -9\% & -10\% -8\% & +0\% -8\% & & \\ & & +1.7 & +1.7 - 0.0095i & -5.7 - 0.0095i & -0.17 - 0.09i & \\ & & -9\% & -8\% -8\% & -8\% -8\% & & \\ & & & +0.64 & -3.9 - 0.029i & -0.098 - 0.068i & \\ & & & -9\% & -9\% -9\% & & \\ & & & & +6.6 & +0.31 + 0.21i & \\ & & & & -9\% & & \\ & & & & & +0.00066 & \\ & & & & & & C_{uG}^{(3a)*} \end{array} \right) \\
& + 0.02 \left(\begin{array}{c} |C_{lequ}^{1(13)}|^2 + |C_{lequ}^{1(31)}|^2 \\ 0\% \end{array} \right) + 0.81 \left(\begin{array}{c} |C_{lequ}^{3(13)}|^2 + |C_{lequ}^{3(31)}|^2 \\ -9\% \end{array} \right)
\end{aligned}$$

- two-quark op.: implemented NLO UFO model [Degrande et al. 14']
 - two-quark–two-lepton op.: analytically then (now in UFO too) [Zhang 14']
 - four-quarks op.: flavour conserving implementation in progress

Four-fermion operators

outdated notation!

[1412.7166]

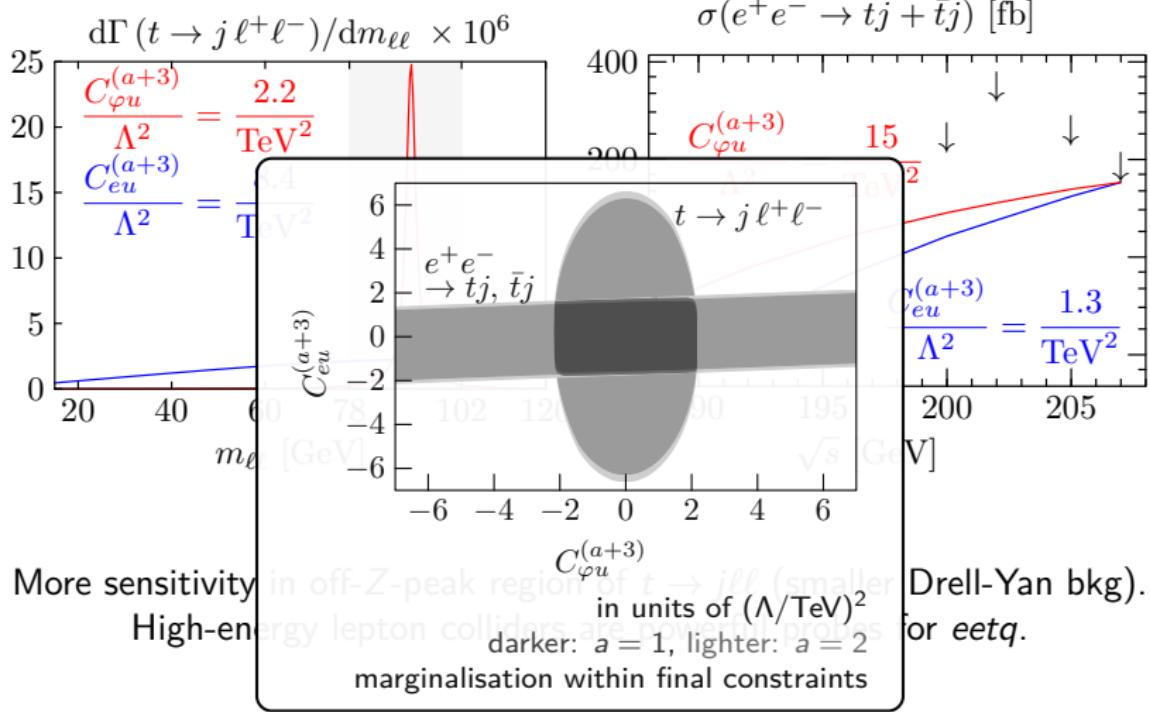


More sensitivity in off-Z-peak region of $t \rightarrow j\ell\ell$ (smaller Drell-Yan bkg).
High-energy lepton colliders are powerful probes for $eetq$.

Four-fermion operators

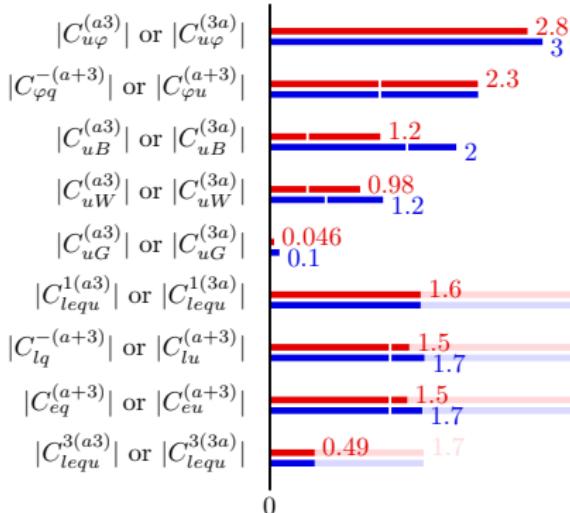
outdated notation!

[1412.7166]



Global constraints at NLO in QCD

[1412.7166]



2014 status
outdated notation!

in units of $(\Lambda/\text{TeV})^2$ red: $a = 1$ (up)blue: $a = 2$ (charm)

white: individual limits

light shades: $\mu\mu tq$

11

Observables:

 $t \rightarrow j\gamma\gamma$ $t \rightarrow j\ell^+\ell^-$ $pp \rightarrow t\gamma, \bar{t}\gamma$ $pp \rightarrow t, \bar{t}$ $e^+e^- \rightarrow tj, \bar{t}j$

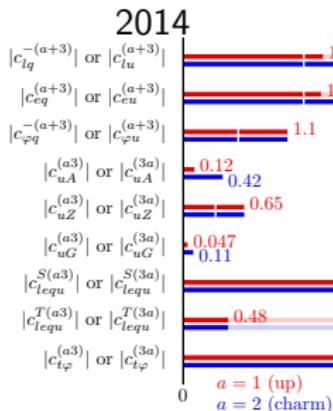
Potential improvements:

- Off-Z-peak region in $t \rightarrow j\ell^+\ell^-$ and update of $pp \rightarrow t\ell^+\ell^-$
- Angular distributions like 'helicity fractions'
- Experimental-grade combination

HL-LHC prospects

[1812.07638]

in LHC TOP WG conventions



vector 4f

vector tqZ

dipoles

tensor 4f

Yukawa

light shades:

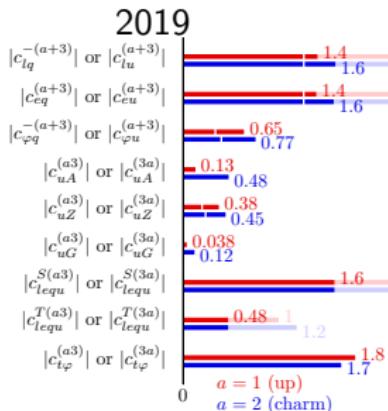
excluding $e^+e^- \rightarrow tq$
to assess $\mu\mu tq$ sensitivity

limited improvement on $eetq$, dominated by LEP2
factors of 2-4 on tqZ, γ, g, h and $\mu\mu tq$ expected from HL-LHC

HL-LHC prospects

[1812.07638]

in LHC TOP WG conventions



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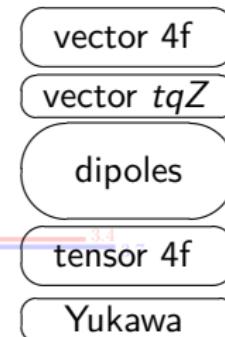
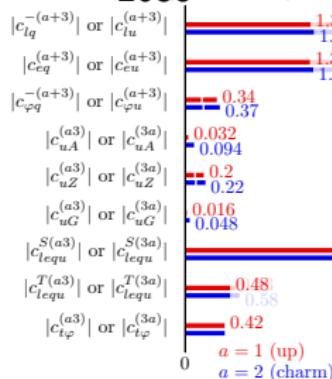
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HL-LHC prospects

[1812.07638]

in LHC TOP WG conventions

2038

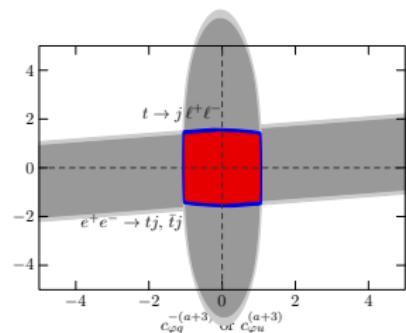


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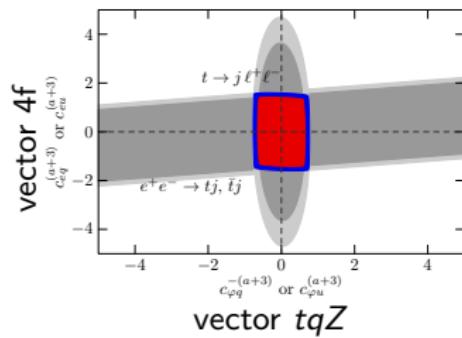
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HL-LHC prospects

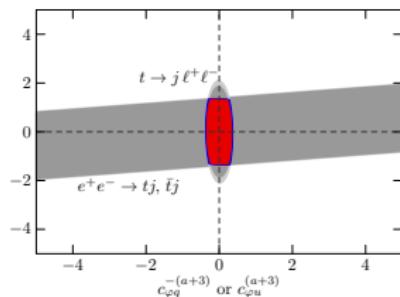
2014



2019



2038



superposed 95% C.L. limits
remaining directions marginalized within final constraints

Other recent studies

- CMS combination of $pp \rightarrow tZ$ and $t \rightarrow qZ$ [CMS-PAS-TOP-17-017 (Nov '17)] with anomalous couplings (no four-fermion operators)
 - $\text{Br}(t \rightarrow e\mu q) < 6.6 \times 10^{-6}$ [ATLAS-CONF-2018-044 (Sep '18)]
What proportion of $q = u, c$ and $\ell = e, \mu, \tau$ in
 $\text{Br}(t \rightarrow \ell\ell' q) < 1.86 \times 10^{-5}$?
- $t \rightarrow \ell\ell^{(\prime)} q$ four-fermion operator prospects [Chala Santiago Spannowsky 1809.09624]
(and $t \rightarrow Zq$ recast for $\mu\mu tc$)

	$c_{lq}^{-(ij23)}$	$c_{eq}^{(ij23)}$	$c_{lu}^{(ij23)}$	$c_{eu}^{(ij23)}$	$c_{lequ}^{1(ij23)}$	$c_{lequ}^{1(ij32)}$	$c_{lequ}^{3(ij23)}$	$c_{lequ}^{3(ij32)}$
$\mu^+ \mu^-$	8.4 (1.0)	8.4 (1.0)	8.4 (1.0)	8.4 (1.0)	18.0 (2.2)	18.0 (2.2)	2.3 (0.28)	2.3 (0.28)
$\mu^\pm e^\mp$	6.3 (1.1)	6.3 (1.1)	6.3 (1.1)	6.3 (1.1)	13.0 (2.4)	13.0 (2.4)	1.7 (0.3)	1.7 (0.3)
$\mu^\pm \tau^\mp$	14.0 (2.0)	14.0 (2.0)	14.0 (2.0)	14.0 (2.0)	29.0 (4.3)	29.0 (4.3)	3.7 (0.55) 3.7 (0.55)	3.7 (0.55)
$e^+ e^-$	10.0 (1.2)	10.0 (1.2)	10.0 (1.2)	10.0 (1.2)	22.0 (2.7)	22.0 (2.7)	2.8 (0.34) 2.8 (0.34)	2.8 (0.34)
$e^\pm \tau^\mp$	15.0 (2.1)	15.0 (2.1)	15.0 (2.1)	15.0 (2.1)	32.0 (4.7)	32.0 (4.7)	4.1 (0.6) 4.1 (0.6)	4.1 (0.6)

individual constraints,
 present: off-Z
 (HL-LHC: off-Z, on-t)

Future lepton collider prospects

[CLIC YR 1812.02093]

[GD in preparation]

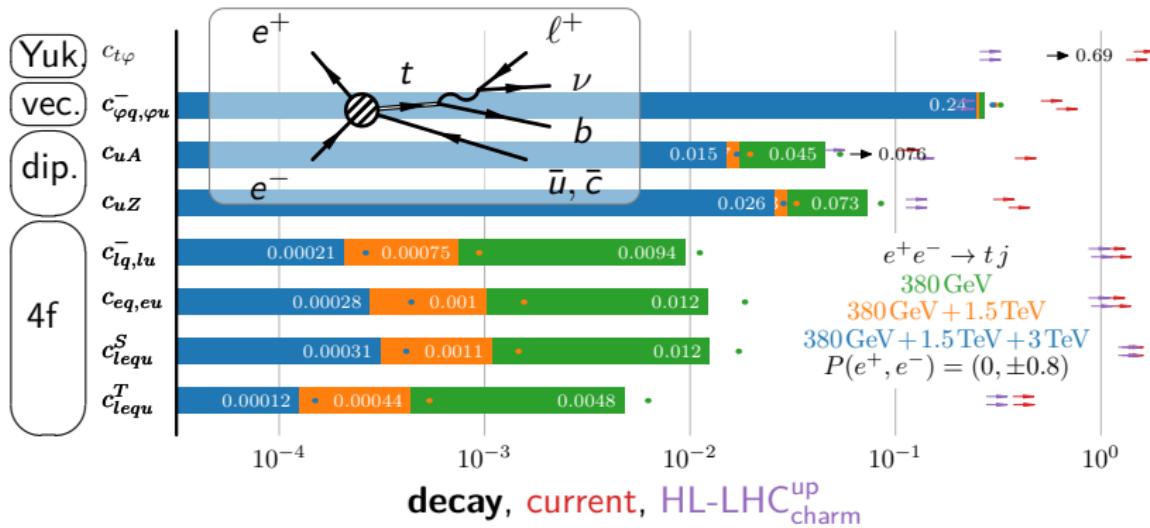
Use *statistically optimal observables*

Extrapolate efficiencies from existing studies

[TESLA: hep-ph/0102197]

[FCC-ee: 1408.2090]

global 95% CL limits, in TeV^{-2} , CLIC scenario (0.5, 1.5, 3 ab^{-1})



decay, current, HL-LHC_{charm}^{up}

more sensitive than FCNC decay

available below $t\bar{t}$ threshold and benefits from high energies

Top-quark FCNCs

Global EFT interpretations are manageable (at NLO in QCD).

Relevant four-fermion operators are still ignored by exp.

Off-Z-peak $m_{\ell\ell}$ regions have enhanced sensitivities.

Production and decay processes are complementary.

Internal anomalous-coupling combinations cannot be
EFT-reinterpreted.

The HL-LHC would bring 2-4 improvements on tqZ, γ, g, h
and $\mu\mu tq$ operator coefficient limits.

Future lepton colliders would dramatically improve $eetq$,
starting from below the $t\bar{t}$ threshold.

Extras

Statistically optimal observables

[Atwood,Soni '92]
[Diehl,Nachtmann '94]

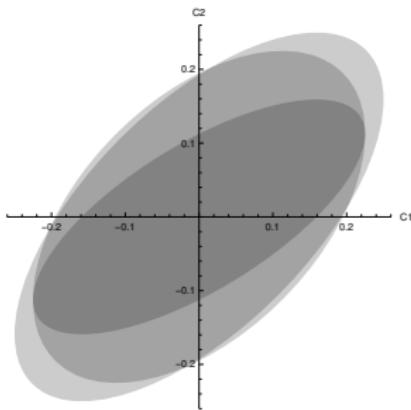
minimize the one-sigma ellipsoid in EFT parameter space

(joint efficient set of estimators, saturating the Cramér-Rao bound: $V^{-1} = I$, like MEM)

For small C_i , with a phase-space distribution $\sigma(\Phi) = \sigma_0(\Phi) + \sum_i C_i \sigma_i(\Phi)$,
the stat. opt. obs. are the average values of $O_i(\Phi) = n \sigma_i(\Phi)/\sigma_0(\Phi)$.

The associated covariance at $C_i = 0, \forall i$ is

$$\text{cov}(C_i, C_j)^{-1} = \epsilon \mathcal{L} \int d\Phi \frac{\sigma_i(\Phi)\sigma_j(\Phi)}{\sigma_0(\Phi)}.$$



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: $O_i \sim \frac{\sin(i\phi)}{1 + \cos\phi}$
- ⇒ area ratios $1.9 : 1.7 : 1$

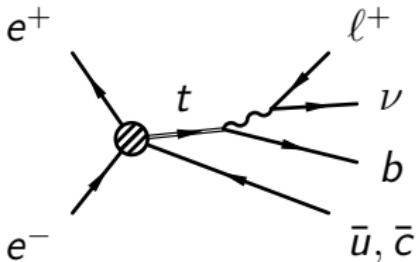
Applications in $e^+e^- \rightarrow t\bar{t}$, on different distributions:

[Grzadkowski, Hioki '00] [Janot '15] [Khiem et al '15] [GD et al '18]

Future lepton collider prospects

[1812.02093] [GD in preparation]

- ▶ Pseudo OO's (quadratic dependence!) vs. WW background
- ▶ Choose ϵ to match existing studies



[TESLA: hep-ph/0102197]

[FCC-ee: 1408.2090]

\sqrt{s} [GeV]	\mathcal{L} [fb^{-1}]	$P(e^+, e^-)$	$\text{Br}(t \rightarrow j\gamma)$ before fit	ϵ before fit	ϵ after fit	Br after fit
240	3000	(0, 0)	3.70×10^{-5}	0.30	0.30	3.7×10^{-5}
350	3000	(0, 0)	9.86×10^{-6}	0.19	0.14	1.1×10^{-5}
500	3000	(0, 0)	6.76×10^{-6}	0.057	0.072	6.0×10^{-6}
500	300	(0, 0)	2.2×10^{-5}	0.054	0.072	1.9×10^{-5}
800	500	(0, 0)	7.8×10^{-6}	0.037	0.029	8.7×10^{-6}

- ▶ Extrapolate to CLIC run parameters and go global
 - $\epsilon = \epsilon(\sqrt{s}) = (125 \text{ GeV}/\sqrt{s})^{1.92}$
 - include four-fermion operators