Global effective-field-theory approach to top-quark FCNCs

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Flavour-changing neutral currents

Vanishingly small in the SM

e.g. top decays:

	$\mathrm{Br}^{\mathrm{SM}}$
$t \to cg$	$\sim 10^{-11}$
$t \to c\gamma$	$\sim 10^{-12}$
$t \to cZ$	$\sim 10^{-13}$
$t \to ch$	$\sim 10^{-14}$

[Eilam et al, 91]
[Mele et al, 98]

Flavour-changing neutral currents

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e.g. top decays:

	$\mathrm{Br}^{\mathrm{SM}}$	$\mathrm{Br}^{\mathrm{exp}}$
$t \to cg$	$\sim 10^{-11}$	$\lesssim 10^{-5*}$
$t \to c\gamma$	$\sim 10^{-12}$	$\lesssim 10^{-3*}$
$t \to cZ$	$\sim 10^{-13}$	$\lesssim 10^{-3}$
$t \to ch$	$\sim 10^{-14}$	$\lesssim 10^{-2}$

*from production processes

vs. about $11 \cdot 10^6$ tops produced at the Tevatron and LHC run I
$+1.6 \cdot 10^6/\mathrm{fb}^{-1}$ at 13 TeV
$+6 \cdot 10^{10}/\mathrm{ab}^{-1}$ at 100 TeV

The effective field theory for top-quark FCNCs

The EFT parametrization of NP

(...) if one writes down the most general possible Lagrangian, including all terms consistent with assumed symmetry principles, (...) the result will simply be the most general possible S-matrix consistent with analyticity, perturbative unitarity, cluster decomposition and the assumed symmetry.

[Weinberg 79]

Assumption:

New-physics states are not directly producible ($\equiv$ low-energy limit).

$\longrightarrow$ use: – SM fields (fermion gauge eigenstates: q, u, d, l, e)
– SM symmetries (gauge and Lorentz)

Advantages:

- relies on few theoretical assumptions
- encodes our knowledge of lower energies
- establishes a hierarchy between NP effects
- is a proper QFT, perturbatively improvable (fixed order, and RG)
- both allows and requires a global treatment

The fermionic SM EFT

dim-3 · no allowed fermion mass term: —

dim-4 · gauge: $\bar{\psi}\not{D}\psi$ and Yukawa: $\bar{\psi}\varphi\psi'$ operators

dim-5 · left-handed neutrino masses ($\Delta L = \pm 2$): $\overline{l^c}\varphi \;\; l\varphi$

dim-6 · four-fermion ($\Delta L = \Delta B = \pm 1$, or 0) [Grzadkowski et al 10']

basis reduction with Fierz and Schouten identities

· two-fermion:

D^μ	φ		
3	0	—	
2	1	$\bar{\psi}\sigma^{\mu\nu}\psi'\varphi \quad X_{\mu\nu}$	Tensor
1	2	$\bar{\psi}\gamma^\mu\psi \quad \varphi^\dagger D_\mu\varphi$	Vector
0	3	$\bar{\psi}\psi'\varphi \quad \varphi^\dagger\varphi$	Scalar

basis reduction with EOMs

dim-7 · $\Delta L \neq 0$: ... [Lehman 14']

...

The up-sector FCNC operators

[Grzadkowski et al 10']

Two-quark operators:

$$
\begin{array}{llcl}
\text{Scalar:} & O_{u\varphi} & \equiv & -y_t^3 \quad \bar{q}\, u\, \tilde{\varphi} \quad (\varphi^\dagger \varphi - v^2/2), \\
\text{Vector:} & [O^+_{\varphi q} + O^-_{\varphi q}]/2 & \equiv & y_t^2/2 \quad \bar{q}\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}_\mu\, \varphi, \\
 & [O^+_{\varphi q} - O^-_{\varphi q}]/2 & \equiv & y_t^2/2 \quad \bar{q}\gamma^\mu \tau^I q \quad \varphi^\dagger i\overleftrightarrow{D}^I_\mu\, \varphi, \\
 & O_{\varphi u} & \equiv & y_t^2/2 \quad \bar{u}\gamma^\mu u \quad \varphi^\dagger i\overleftrightarrow{D}_\mu\, \varphi, \\
\text{Tensor:} & O_{uB} & \equiv & y_t g_Y \quad \bar{q}\sigma^{\mu\nu} u\, \tilde{\varphi} \quad B_{\mu\nu}, \\
 & O_{uW} & \equiv & y_t g_W \quad \bar{q}\sigma^{\mu\nu}\tau^I u\, \tilde{\varphi} \quad W^I_{\mu\nu}, \\
 & O_{uG} & \equiv & y_t g_s \quad \bar{q}\sigma^{\mu\nu} T^A u\, \tilde{\varphi} \quad G^A_{\mu\nu}.
\end{array}
$$

Two-quark–two-lepton operators:

$$
\begin{array}{llcl}
\text{Scalar:} & O^1_{lequ} & \equiv & \bar{l}\, e \;\; \varepsilon \;\; \bar{q}\, u, \\
\text{Vector:} & [O^+_{lq} + O^-_{lq}]/2 & \equiv & \bar{l}\gamma_\mu l \quad \bar{q}\gamma^\mu q, \\
 & [O^+_{lq} - O^-_{lq}]/2 & \equiv & \bar{l}\gamma_\mu \tau^I l \quad \bar{q}\gamma^\mu \tau^I q, \\
 & O_{lu} & \equiv & \bar{l}\gamma_\mu l \quad \bar{u}\gamma^\mu u, \\
 & O_{eq} & \equiv & \bar{e}\gamma^\mu e \quad \bar{q}\gamma_\mu q, \\
 & O_{eu} & \equiv & \bar{e}\gamma_\mu e \quad \bar{u}\gamma^\mu u, \\
\text{Tensor:} & O^3_{lequ} & \equiv & \bar{l}\sigma_{\mu\nu} e \quad \varepsilon \quad \bar{q}\sigma^{\mu\nu} u.
\end{array}
$$

Four-quark operators: ...

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

Independent coefficients for top FCNCs

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

Scalar: $C_{u\varphi}^{(a3)},\ C_{u\varphi}^{(3a)},$

Vector:

$$C_{\varphi q}^{+(a3)} = C_{\varphi q}^{+(3a)*} \equiv C_{\varphi q}^{+(a+3)}, \qquad \text{(down-}Z\text{)}$$
$$C_{\varphi q}^{-(a3)} = C_{\varphi q}^{-(3a)*} \equiv C_{\varphi q}^{-(a+3)}, \qquad \text{(up-}Z\text{)}$$
$$C_{\varphi u}^{(a3)} = C_{\varphi u}^{(3a)*} \equiv C_{\varphi u}^{(a+3)},$$

Tensor:

$$C_{uB}^{(a3)},\ C_{uB}^{(3a)},$$
$$C_{uW}^{(a3)},\ C_{uW}^{(3a)},$$
$$C_{uG}^{(a3)},\ C_{uG}^{(3a)}.$$

Two-quark–two-lepton operators: $8 \times 2 \times 3^2$ complex coefficients

Scalar: $C_{lequ}^{1(a3)},\ C_{lequ}^{1(3a)},$

Vector:

$$C_{lq}^{+(a3)} = C_{lq}^{+(3a)*} \equiv C_{lq}^{+(a+3)}, \qquad \text{(up–}\nu\text{, down–}\ell\text{)}$$
$$C_{lq}^{-(a3)} = C_{lq}^{-(3a)*} \equiv C_{lq}^{-(a+3)}, \qquad \text{(up–}\ell\text{, down–}\nu\text{)}$$
$$C_{lu}^{(a3)} = C_{lu}^{(3a)*} \equiv C_{lu}^{(a+3)}, \qquad \text{(up–}\ell\text{, up–}\nu\text{)}$$
$$C_{eq}^{(a3)} = C_{eq}^{(3a)*} \equiv C_{eq}^{(a+3)}, \qquad \text{(up–}\ell\text{, down–}\ell\text{)}$$
$$C_{eu}^{(a3)} = C_{eu}^{(3a)*} \equiv C_{eu}^{(a+3)},$$

Tensor: $C_{lequ}^{3(a3)},\ C_{lequ}^{3(3a)}.$

Four-quark operators: ...

Gauge vs. physical basis

Gauge-invariant operators are constructed from gauge eigenstates.

$$q \equiv (P_L u, \boldsymbol{V}_{\text{CKM}} P_L d)^T, \qquad u \equiv P_R u, \qquad d \equiv P_R d,$$
$$l \equiv (\boldsymbol{V}_{\text{PMNS}} P_L \nu, P_L e)^T, \qquad e \equiv P_R e$$

The coefficients of physical eigenstate operators in the left-handed sector are related by V_{CKM} (and V_{PMNS}), *e.g.*

$$\begin{aligned} C^-_{lq} O^-_{lq} = {} & [V^\dagger_{\text{PMNS}} V^\dagger_{\text{CKM}} C^-_{lq} V_{\text{CKM}} V_{\text{PMNS}}]^a{}_b{}^c{}_d \quad (\bar\nu_a \gamma^\mu P_L \nu^b \quad \bar d_c \gamma_\mu P_L d^d) \\ & + [C^-_{lq}]^a{}_b{}^c{}_d \quad (\bar e_a \gamma^\mu P_L e^b \quad \bar u_c \gamma_\mu P_L u^d) \end{aligned}$$

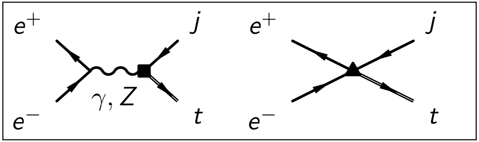
Numerically, e.g.

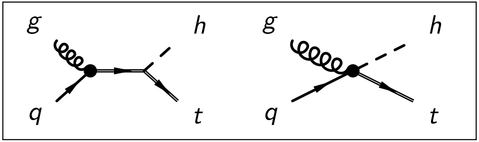
$$[V^\dagger_{\text{CKM}} C V_{\text{CKM}}]^3{}_1 \simeq 0.88\ C^3{}_1 - 0.47\ C^3{}_2 + 0.04\ C^2{}_1 + \ldots$$

The broken-phase effective Lagrangian

Schematically:

Scalar:	$\bar{t}q$	h
Vector:	$\bar{t}\gamma^\mu q$	Z_μ
Tensor:	$\bar{t}\sigma^{\mu\nu}q$	$A_{\mu\nu}$
	$\bar{t}\sigma^{\mu\nu}q$	$Z_{\mu\nu}$
	$\bar{t}\sigma^{\mu\nu}T^A q$	$G^A_{\mu\nu}$





Issues:

1. Missing four-point interactions:
   - four-fermion operators
   - a *tqgh* vertex arising from $O_{uG} \equiv \bar{q}\sigma^{\mu\nu}T^A u\ \tilde{\varphi}\quad G^A_{\mu\nu}$
2. Operators of seemingly different dimensions
3. Missed correlations:
   of '$v + h$' type
   of '$(t_L \quad [V_{\text{CKM}} d_L]^3)^T$' type

A first global EFT analysis at NLO in QCD

Direct searches

			tqg, T	$tqgh$ T	$tq\gamma$ T	tqZ V,T	$tq\ell\ell$ S,V,T	$tqqq$ S,V,T	tqh S
The broken-phase effective Lagrangian:			✓	✗	✓	✓,✓	✗	✗	✓
production	• $e^+e^- \to t\,j$	OPAL, DELPHI, ALEPH, L3			✓	✓,✗	✗		
	$e^-p \to e^-t$	**H1**, ZEUS			✓	✗	✗		
	• $p\overset{(-)}{p} \to t$	CDF, **ATLAS**	✓						
	$p\overset{(-)}{p} \to t\,j$	D0, **CMS**	✓		✗	✗		✗	
	• $p\,p \to t\,\gamma$	CMS	✗		✓				
	$p\,p \to t\,\ell^+\ell^-$	CMS	✓		✗	✗,✓	✗		
	$p\,p \to t\,\gamma\gamma$	—	✗	✗	✗				✗
decay	$t \to j\gamma$	**CDF**, D0, ATLAS, CMS			✓				
	• $t \to j\ell^+\ell^-$	CDF, D0, ATLAS, **CMS**			✗	✓,✗	✗		
	• $t \to j\gamma\gamma$	**CMS**, ATLAS			✗				✓

One single contribution is often assumed, although:

- NP could generate several operators at Λ.
- RG mixings (and fixed order corrections) would contaminate more of them at E.
- EOM, Fierz identities, etc. have converted some op. into combinations of others.

$\Longrightarrow$ A consistent EFT treatment should include *all* operators up to a given dimension!

Interferences and NLO

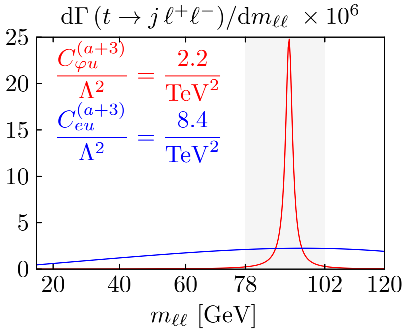
e.g. $$\Gamma^{m_{\ell\ell}\in[78,102]\text{ GeV}}_{t\to j\,\ell^+\ell^-} = 10^{-5}\text{ GeV} \times \left(\frac{1\text{ TeV}}{\Lambda}\right)^4 \times$$

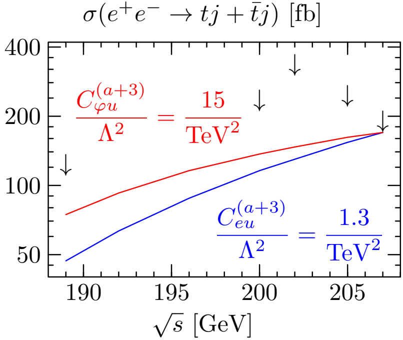
$$\text{Re}\begin{pmatrix} C_{lq}^{-(a+3)} \\ C_{eq}^{(a+3)} \\ C_{\varphi q}^{-(a+3)} \\ C_{uB}^{(a3)} \\ C_{uW}^{(a3)} \\ C_{uG}^{(a3)} \end{pmatrix}^\dagger \begin{pmatrix} \underset{-9\%}{+0.069} & 0 & \underset{+6\%}{-0.02} - \underset{-9\%}{0.2}\,i & \underset{-5\%}{-0.053} - \underset{-8\%}{0.1}\,i & \underset{-16\%}{-0.052} + \underset{-8\%}{0.34}i & \underset{—}{+0.014} - \underset{—}{0.013}i \\ & \underset{-9\%}{+0.069} & \underset{+6\%}{+0.017} + \underset{-9\%}{0.18}i & \underset{-10\%}{-0.053} + \underset{-8\%}{0.09}i & \underset{+0\%}{-0.054} - \underset{-8\%}{0.3}\,i & \underset{—}{-0.007} + \underset{—}{0.017}i \\ & & \underset{-9\%}{+1.7} & \underset{-8\%}{+1.7} - \underset{-8\%}{0.0095}i & \underset{-8\%}{-5.7} - \underset{-8\%}{0.0095}i & \underset{—}{+0.27} + \underset{—}{0.2}i \\ & & & \underset{-9\%}{+0.64} & \underset{-9\%}{-3.9} - \underset{-9\%}{0.029}i & \underset{—}{+0.16} + \underset{—}{0.14}i \\ & & & & \underset{-9\%}{+6.6} & \underset{—}{-0.53} - \underset{—}{0.47}i \\ & & & & & \underset{—}{+0.002} \end{pmatrix} \begin{pmatrix} C_{lq}^{-(a+3)} \\ C_{eq}^{(a+3)} \\ C_{\varphi q}^{-(a+3)} \\ C_{uB}^{(a3)} \\ C_{uW}^{(a3)} \\ C_{uG}^{(a3)} \end{pmatrix}$$

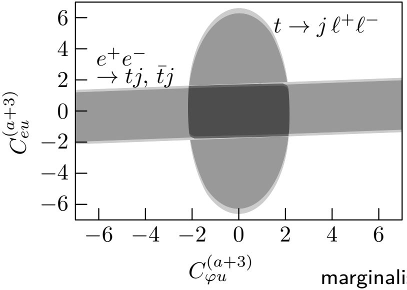
$$+\text{Re}\begin{pmatrix} C_{lu}^{(a+3)} \\ C_{eu}^{(a+3)} \\ C_{\varphi u}^{(a+3)} \\ C_{uB}^{(3a)*} \\ C_{uW}^{(3a)*} \\ C_{uG}^{(3a)*} \end{pmatrix}^\dagger \begin{pmatrix} \underset{-9\%}{+0.069} & 0 & \underset{+6\%}{-0.02} - \underset{-9\%}{0.2}\,i & \underset{-5\%}{-0.053} - \underset{-8\%}{0.1}\,i & \underset{-16\%}{-0.052} + \underset{-8\%}{0.34}i & \underset{—}{-0.002} + \underset{—}{0.013}i \\ & \underset{-9\%}{+0.069} & \underset{+6\%}{+0.017} + \underset{-9\%}{0.18}i & \underset{-10\%}{-0.053} + \underset{-8\%}{0.09}i & \underset{+0\%}{-0.054} - \underset{-8\%}{0.3}\,i & \underset{—}{+0.0067} - \underset{—}{0.006}i \\ & & \underset{-9\%}{+1.7} & \underset{-8\%}{+1.7} - \underset{-8\%}{0.0095}i & \underset{-8\%}{-5.7} - \underset{-8\%}{0.0095}i & \underset{—}{-0.17} - \underset{—}{0.09}i \\ & & & \underset{-9\%}{+0.64} & \underset{-9\%}{-3.9} - \underset{-9\%}{0.029}i & \underset{—}{-0.098} - \underset{—}{0.068}i \\ & & & & \underset{-9\%}{+6.6} & \underset{—}{+0.31} + \underset{—}{0.21}i \\ & & & & & \underset{—}{+0.00066} \end{pmatrix} \begin{pmatrix} C_{lu}^{(a+3)} \\ C_{eu}^{(a+3)} \\ C_{\varphi u}^{(a+3)} \\ C_{uB}^{(3a)*} \\ C_{uW}^{(3a)*} \\ C_{uG}^{(3a)*} \end{pmatrix}$$

$$+\underset{0\%}{0.02}\left(|C_{lequ}^{1(13)}|^2 + |C_{lequ}^{1(31)}|^2\right) + \underset{-9\%}{0.81}\left(|C_{lequ}^{3(13)}|^2 + |C_{lequ}^{3(31)}|^2\right)$$

Four-fermion operators



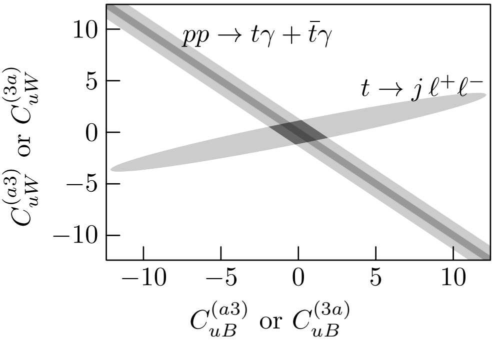


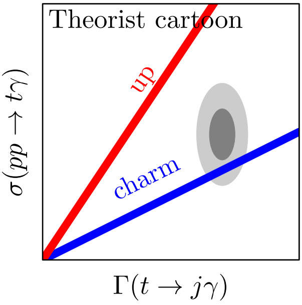


in units of $(\Lambda/\mathrm{TeV})^2$
darker: $a = 1$, lighter: $a = 2$
marginalisation within final constraints

Production vs. decay

Discriminate the *tc* and *tu* interactions through proton PDF.





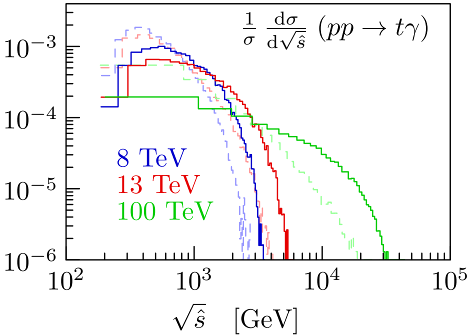
$C_{uA} \equiv C_{uW} + C_{uB}$
$C_{uZ} \equiv C_{uW}\ \cot\theta_W - C_{uB}\ \tan\theta_W$

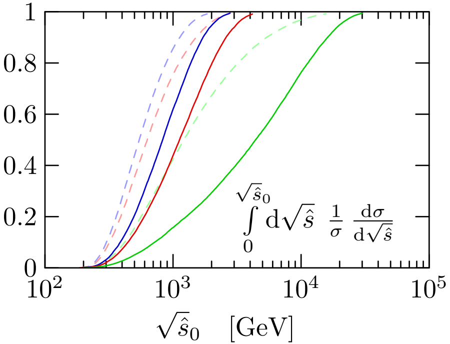
in units of $(\Lambda/\text{TeV})^2$
darker: $a = 1$ (up), lighter: $a = 2$ (charm)
marginalising within C_{uG} constraints

Production vs. decay

Probing higher energies...

solid: $a = 1$ (up)
dashed: $a = 2$ (charm)





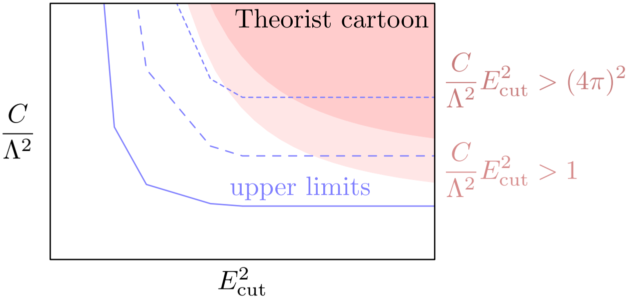
...until the EFT breaks down.

Validity of the EFT

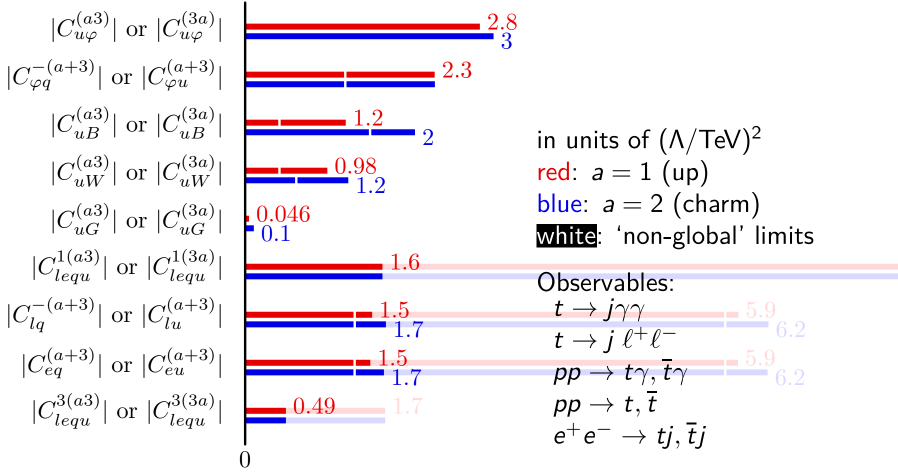
New-physics states should not be directly producible
$\equiv$ low-energy limit

Providing bounds as a function of a cut on the characteristic energy scale of the process E makes them interpretable for cutoffs lower than the experiment energy reach. [Contino et al 16']

A E_{cut} may be required: · for EFT perturbativity
· for insuring [SM-EFT interference] $<$ [EFT]^2



Global constraints at NLO in QCD (as of ICHEP 2016)



Experimental improvements:

- Off-Z-peak region in $t \to j\,\ell^+\ell^-$ and update of $pp \to t\,\ell^+\ell^-$
- Constraint on $pp \to th$
- Statistical combinations
- Angular distributions like 'helicity fractions'

Summary

High statistics allows for precision tests in the top sector.
Higher energies give sensitivity to heavier new physics.

A fully gauge-invariant EFT permits an accurate interpretation of the data in terms of well-defined QFT parameters.

Precise constraints can be set globally in the EFT, as they should.

A combination with observables from other sectors, the B sector notably, is also possible.