EFT for top-quark FCNCs

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Global approach to top-quark flavor-changing interactions
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Flavour-changing neutral currents

Vanishingly small in the SM

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

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:

Scalar: $O_{u\varphi} \equiv -y_t^3 \quad \bar{q}\, u\, \tilde{\varphi} \quad (\varphi^\dagger \varphi - v^2/2),$

Vector:

$$[O^+_{\varphi q} + O^-_{\varphi q}]/2 \equiv y_t^2/2 \quad \bar{q}\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi,$$

$$[O^+_{\varphi q} - O^-_{\varphi q}]/2 \equiv y_t^2/2 \quad \bar{q}\gamma^\mu \tau^I q \quad \varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi,$$

$$O_{\varphi u} \equiv y_t^2/2 \quad \bar{u}\gamma^\mu u \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi,$$

Tensor:

$$O_{uB} \equiv y_t g_Y \quad \bar{q}\sigma^{\mu\nu} u\, \tilde{\varphi} \quad B_{\mu\nu},$$

$$O_{uW} \equiv y_t g_W \quad \bar{q}\sigma^{\mu\nu}\tau^I u\, \tilde{\varphi} \quad W^I_{\mu\nu},$$

$$O_{uG} \equiv y_t g_s \quad \bar{q}\sigma^{\mu\nu} T^A u\, \tilde{\varphi} \quad G^A_{\mu\nu}.$$

Two-quark–two-lepton operators:

Scalar: $O^1_{lequ} \equiv \bar{l}\, e \;\varepsilon\; \bar{q}\, u,$

Vector:

$$[O^+_{lq} + O^-_{lq}]/2 \equiv \bar{l}\gamma_\mu l \quad \bar{q}\gamma^\mu q,$$

$$[O^+_{lq} - O^-_{lq}]/2 \equiv \bar{l}\gamma_\mu \tau^I l \quad \bar{q}\gamma^\mu \tau^I q,$$

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

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

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

Tensor: $O^3_{lequ} \equiv \bar{l}\sigma_{\mu\nu} e \quad \varepsilon \quad \bar{q}\sigma^{\mu\nu} u.$

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:

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

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

Four-quark operators: ...

The broken-phase effective Lagrangian

Schematically:

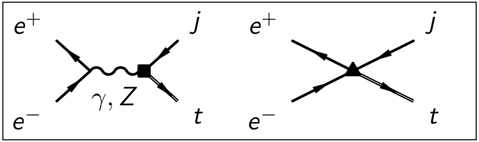
Scalar: $\bar{t} q \quad h$

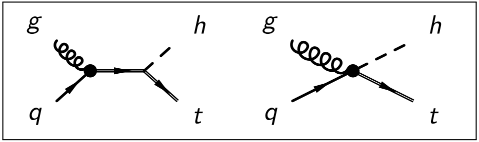
Vector: $\bar{t} \gamma^{\mu} q \quad Z_{\mu}$

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

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

$\bar{t} \sigma^{\mu\nu} T^A q \quad G^A_{\mu\nu}$





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			✓	✓,✗	✗		
production	$e^- p \to e^- t$	**H1**, ZEUS			✓	✗	✗		
production	• $p\overset{(-)}{p} \to t$	CDF, **ATLAS**	✓						
production	$p\overset{(-)}{p} \to t\, j$	D0, **CMS**	✓		✗	✗		✗	
production	• $p\, p \to t\, \gamma$	CMS	✗		✓				
production	$p\, p \to t\, \ell^+\ell^-$	CMS	✓		✗	✗,✓	✗		
production	$p\, p \to t\, \gamma\gamma$	—	✗	✗	✗				✗
decay	$t \to j\gamma$	**CDF**, D0, ATLAS, CMS			✓				
decay	• $t \to j\ell^+\ell^-$	CDF, D0, ATLAS, **CMS**			✗	✓,✗	✗		
decay	• $t \to j\gamma\gamma$	**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. $\Gamma_{t\to j\,\ell^+\ell^-}^{m_{\ell\ell}\in[78,102]\text{ GeV}} = 10^{-5}\text{ GeV} \times \left(\frac{1\text{ TeV}}{\Lambda}\right)^4 \times$

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

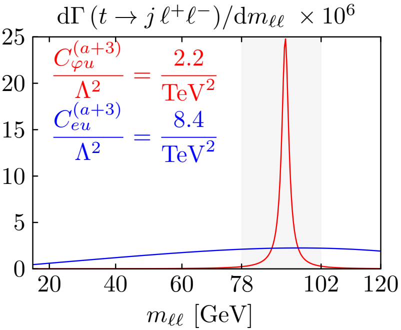
$$
+\mathrm{Re}\begin{pmatrix} C_{lu}^{(a+3)} \\ C_{eu}^{(a+3)} \\ C_{\varphi u}^{(a+3)} \\ C_{uB}^{(3a)*} \\ C_{uW}^{(3a)*} \\ C_{uG}^{(3a)*} \end{pmatrix}^{\dagger}
\begin{pmatrix}
\underset{-9\%}{+0.069} & 0 & \underset{+6\%}{-0.02} - \underset{-9\%}{0.2}\,i & \underset{-5\%}{-0.053} - \underset{-8\%}{0.1}\,i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

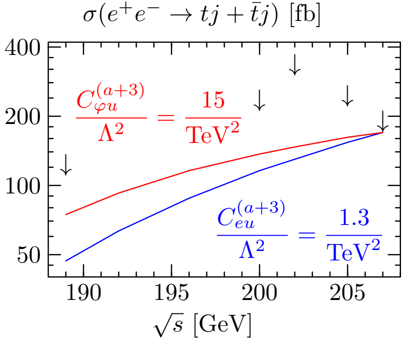
$$
\underset{0\%}{+0.02}\left(|C_{lequ}^{1(13)}|^2 + |C_{lequ}^{1(31)}|^2\right) + \underset{-9\%}{0.81}\left(|C_{lequ}^{3(13)}|^2 + |C_{lequ}^{3(31)}|^2\right)
$$

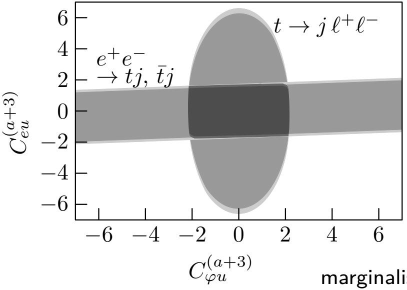
- two-quark op.: implemented NLO UFO model [Degrande et al. 14']
- two-quark–two-lepton op.: analytically then (now in UFO too) [Zhang 14']
- four-quarks op.: implementation in progress

⟶ everything to appear in UFO

Four-fermion operators







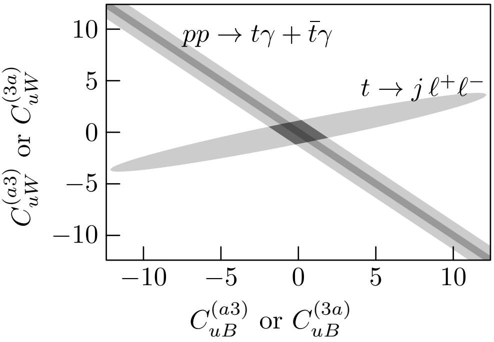
in units of $(\Lambda/\mathrm{TeV})^2$

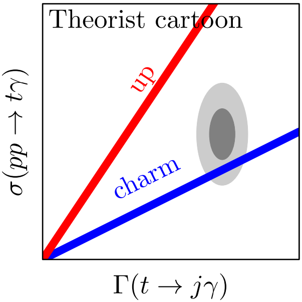
darker: $a = 1$, lighter: $a = 2$

marginalisation within final constraints

Production vs. decay

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





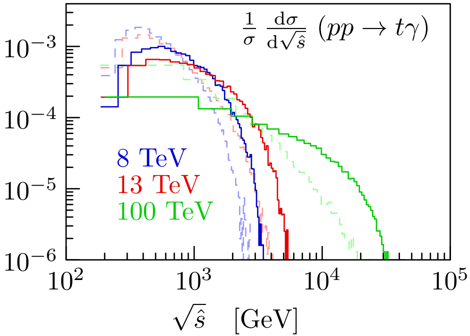
$C_{uA} \equiv C_{uW} + C_{uB}$
$C_{uZ} \equiv C_{uW}\ \cot\theta_W - C_{uB}\ \tan\theta_W$

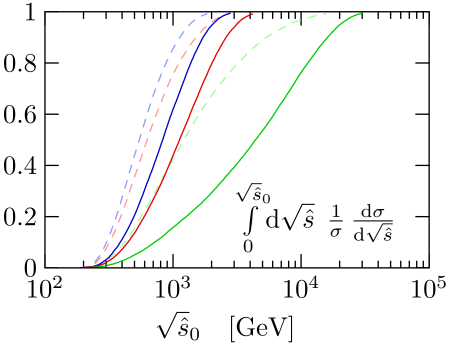
in units of $(\Lambda/\mathrm{TeV})^2$
darker: $a = 1$ (up), lighter: $a = 2$ (charm)
marginalising within C_{uG} constraints

Production vs. decay

Probing higher energies...

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





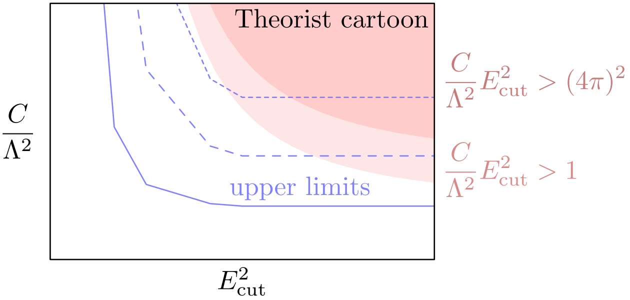
...until the EFT breaks down.

Validity of the EFT

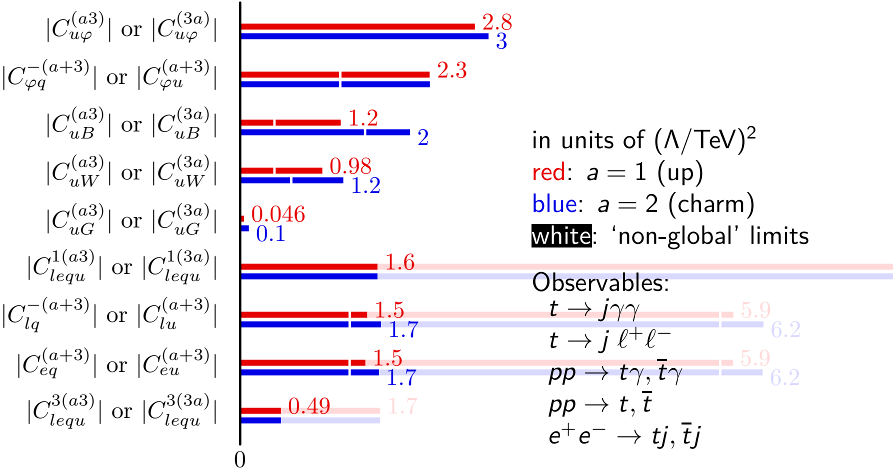
New-physics states should not be directly producible
$\equiv$ low-energy limit

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] $\lesssim$ [EFT]^2



Global constraints at NLO in QCD



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'

How to proceed further?

LHC observables

		tqg	$tqgh$	$tq\gamma$	tqZ	$tq\ell\ell$	$tqqq$	tqh
		T	T	T	V,T	S,V,T	S,V,T	S
Anomalous couplings:		✓		✓	✓,✓			✓
production	$p\,p \to t\,(j)$	✗		(✗)	(✗)		(✗)	
	$p\,p \to t\,\gamma$	✗		✗				
	$p\,p \to t\,\ell^+\ell^-$	✗		✗	✗,✗	✗		
	$p\,p \to t\,\gamma\gamma$	✗	✗	✗				✗
decay	$t \to j\gamma$	✗ (grey)		✗				
	$t \to j\ell^+\ell^-$	✗ (grey)		✗	✗,✗	✗		
	$t \to j\gamma\gamma$	✗ (grey)	✗ (grey)	✗				✗

✗: appearing at LO

✗ (grey): appearing at NLO in QCD

- ! ‘decay’ is formally QCD correction to ‘production’
- separating on-Z-peak and off-Z-peak, separating e^+e^- and $\mu^+\mu^-$
- separating t and $\bar{t}$ (e.g. enhances tug sensitivity, + CPV)

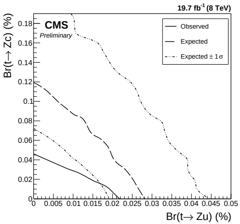
Cut-and-count vs. MVA

! Theory will improve.

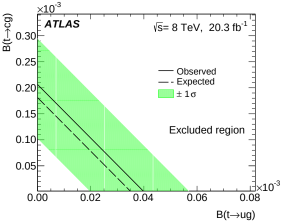
EXP×TH factorisation is desirable

- Fiducial (particle-level) bgd+obs. event counts (and limits) are the simplest way to go.

  eg: $\sigma(pp \to \bar{b}\ell^- \not{E}_T \;\; (j)\ell^+\ell^-)$
  - relatively straightforward to compare prediction to
  - trivial scaling with number of th. parameters
  - theory independent



- More sophistications necessary in some cases
  - bad scaling with number of th. parameters
  - given some means of extrapolation/morphing
  - publishing MVA training



? Systematics uncertainties and correlations
  - between measurements
  - between experiments

Conclusions ...

... are to be draw together.

So, let's discuss!