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

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Global EFT approach to top FCNCs

The effective field theory for top-quark FCNCs

A first global EFT analysis, at NLO in QCD

Top+Higgs FCNC production

Flavour-changing neutral currents

Vanishingly small in the SM

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

e.g. top decays:

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

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

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:

- encodes the knowledge gained at lower energies
- relies on few theoretical assumptions

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]

- establishes a hierarchy between NP effects
- is a proper QFT, as qualified as the dim≤ 4 SM
- is perturbatively improvable (fixed order, and RG)

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	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: $9 \times 2 \times 3^2$ 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

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

so that, *e.g.*:

$$C^-_{lq} O^-_{lq} = [V^\dagger_{\text{PMNS}} V^\dagger_{\text{CKM}} C^-_{lq} V_{\text{CKM}} V_{\text{PMNS}}]^a{}_b{}^c{}_d \quad (\bar{\nu}_a \gamma^\mu P_L \nu^b \quad \bar{d}_c \gamma_\mu P_L d^d)$$
$$+ [C^-_{lq}]^a{}_b{}^c{}_d \qquad (\bar{e}_a \gamma^\mu P_L e^b \quad \bar{u}_c \gamma_\mu P_L u^d)$$

with, e.g.:

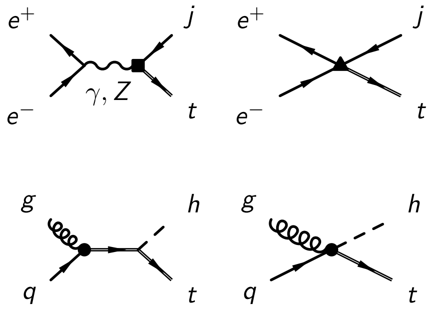
$$[V^\dagger_{\text{CKM}} C V_{\text{CKM}}]^3{}_1 \simeq 0.88\ C^3{}_1 - 0.47\ C^3{}_2 + 0.04\ C^2{}_1 + \ldots$$

A first global EFT analysis at NLO in QCD

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. Hidden correlation:
   of '$v + h$' type
   of '$(t_L \quad [V_{CKM} d_L]^3)^T$' type

Existing 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!

A first global analysis, at NLO in QCD

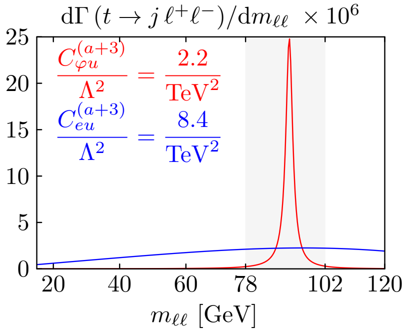
Use the fully gauge-invariant EFT.

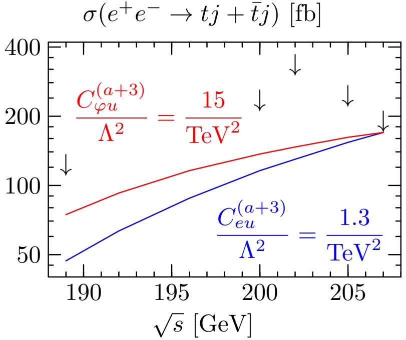
Take all contributions simultaneously into account,
their correlations and interferences.
[not the NLO or vetoed contributions of four-quark operators]

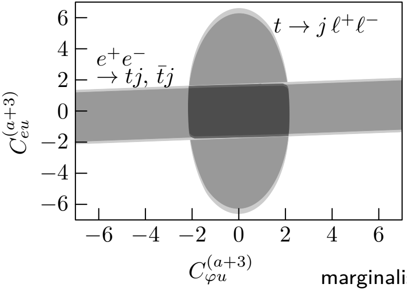
Achieve full NLO accuracy in QCD.

- All two-quark operators are implemented in MG5–aMC@NLO.
  [Degrande et al 14']
  $\longrightarrow$ fully differential, automated NLO+PS production
- Two-quark–two-lepton operators have been added.
  Work on four-quark operators is under way.
- Resonant top quark with NLO and off-shell decay is not available.
  All NLO partial width are however known analytically. [Zhang 14']

Four-fermion operators



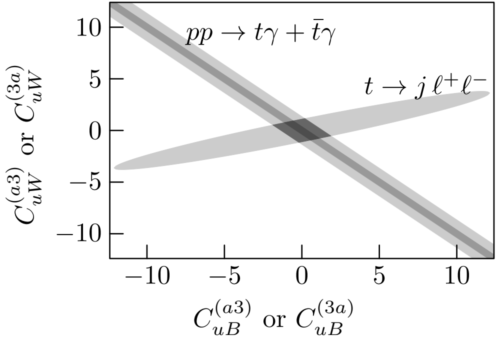


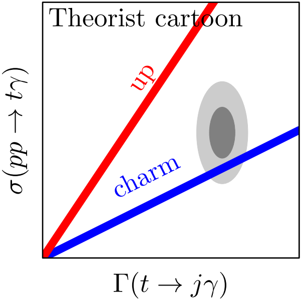


in units of $(\Lambda/\text{TeV})^2$
darker: $a = 1$, lighter: $a = 2$
marginalisation within final constraints

Production vs. decay

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





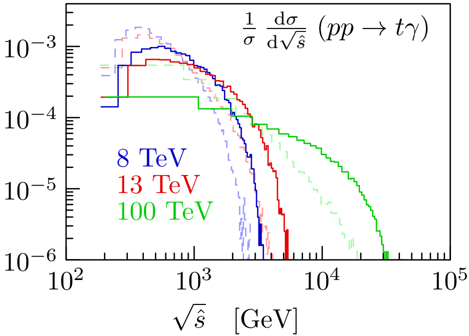
$C_{uA} \equiv C_{uW} + C_{uB}$
$C_{uZ} \equiv C_{uW}\ \cot\theta_W - C_{uB}\ \tan\theta_W$

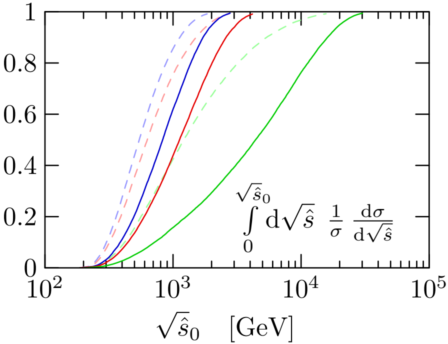
in units of $(\Lambda/\text{TeV})^2$
darker: $a = 1$ (up), lighter: $a = 2$ (charm)
marginalising within C_{uG} constraints

Production vs. decay

Probing higher energies...

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



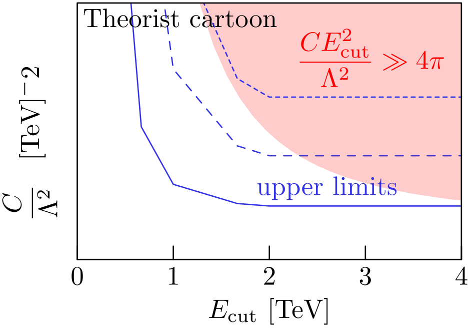


...until the EFT breaks down.

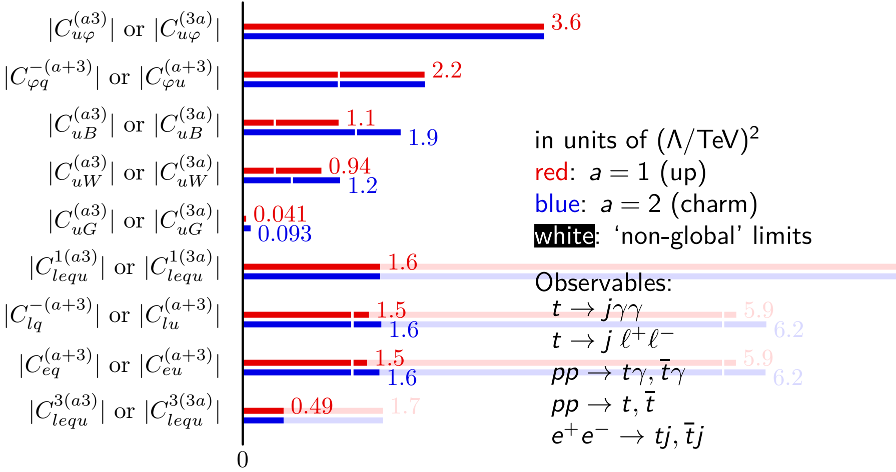
Validity of the EFT

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
$\longrightarrow$ makes them interpretable for cutoffs lower than the experiment energy reach. [Contino et al 16']



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'

Conclusions

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

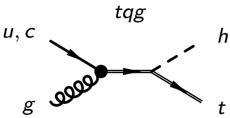
A fully gauge-invariant EFT permits an accurate interpretation of the data in terms of generic parameters.

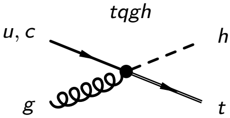
Direct FCNC constraints can be set globally, as they should.

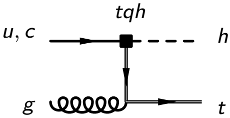
A combination with observables from other sectors, the B sector notably, is possible.

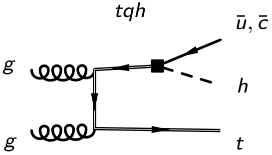
Top+Higgs FCNC production

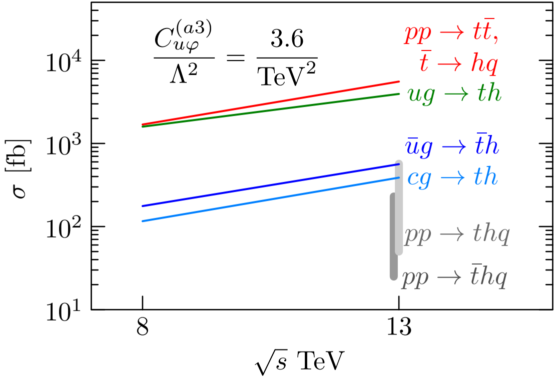
Top+Higgs FCNC production











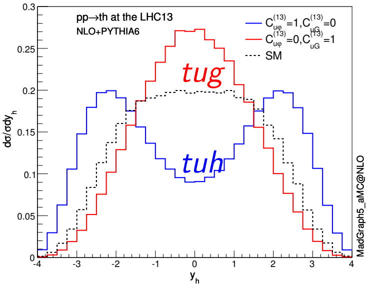
Discriminating tqg and tqh

Use the relative proportion of $pp \to t$

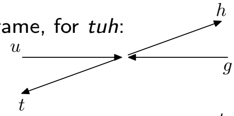
$pp \to th + \bar{t}h$

Use $|\eta_h|$ in $pp \to th + \bar{t}h$

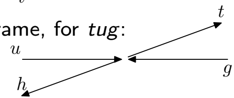
[Degrande, Maltoni, Wang, Zhang 14']



In the rest-frame, for tuh:



In the rest-frame, for tug:



The PDF favours $E_u > E_g$ in the lab-frame

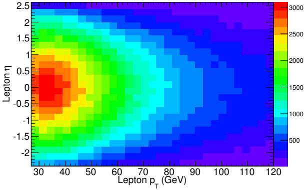
Discriminating up- and charm-top FCNCs

Use the relative proportion of $pp \to t\bar{t},\ \bar{t} \to hj$
$pp \to th$

Use the $pp \to th/\bar{t}h$ asymmetry

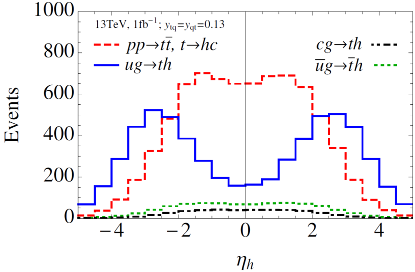
[Khatibi, Najafabadi 14']

- generated by up-top only
- measurable with lept. t decay and h reco.
  or, through $\sum Q_\ell$ with lept. t and h decays
- increasing with $p_{T\ell}$ or $|\eta_\ell|$



Use $|\eta_h|$ if h reco., or $|\eta_{\ell^+\ell^-}|$ in multileptons

[Greljo, Kamenik, Kopp, 14']



Conclusions

A dedicated experimental search for $pp \to th$ is still lacking.

A significant improvement on the 'tuh' bound would derive.

Several features of a signal
could serve to disentangle its components.