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

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LHC Physics Discussion
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I hope to convince you that ...

The EFT parametrization of deviations from the SM
is elegant and powerful
but should be *global* to be consistent.

... through this top FCNC *showcase* example.

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.

[*Phenomenological Lagrangians*, Weinberg, 1979]

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)

and include *all* operators up to a given dimension.

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)

The global EFT analysis strategy

Include simultaneously all operators!

Combine observables!

Offer yourself NLO precision!

Flavour-changing neutral currents

Top FCNCs are vanishingly small in the SM!

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

e.g. top decays:

	Br^{SM}	Br^{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
$+\, 1.6 \cdot 10^6/\text{fb}^{-1}$ at 13 TeV
$+\, 6 \cdot 10^{10}/\text{ab}^{-1}$ at 100 TeV

Constructing 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) [Buchmüller-Wyler 86']

basis reduction with Fierz and Schouten identities [Grzadkowski et al 10']

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

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

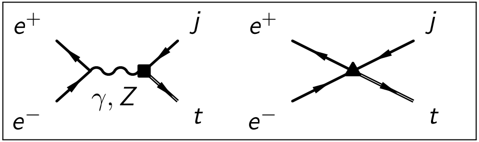
Tensor: $C_{lequ}^{3(a3)}$, $C_{lequ}^{3(3a)}$.

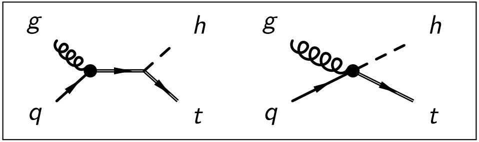
Four-quark operators: ...

The broken-phase effective Lagrangian

Schematically:

Scalar:	$\bar{t}q$	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

Direct searches and their interpretation

			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!

All operators and NLO QCD corrections

e.g., $\Gamma^{m_{\ell\ell}\in[78,102]\ \mathrm{GeV}}_{t\to j\,\ell^+\ell^-}$

$$
10^{-5}\ \mathrm{GeV}\times\left(1\ \mathrm{TeV}\big/\Lambda\right)^4\times
$$

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

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

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

MadGraph for NLO QCD in the effective field theory

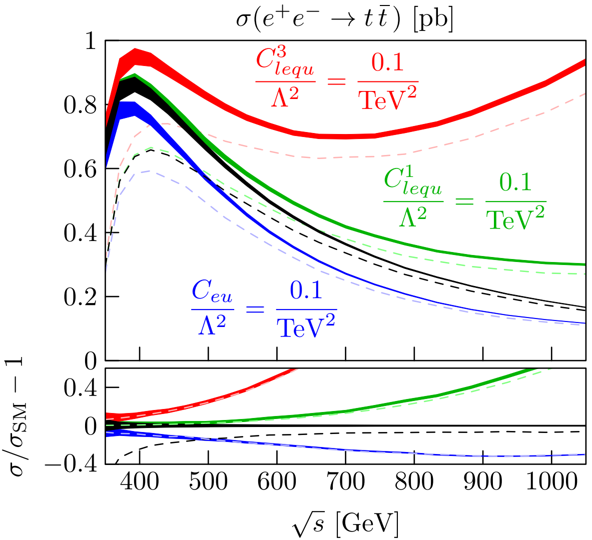
- The implementation of operators is required (UV and R2 CTs). Automation is in progress. [Degrande 14']
    - FCNCs [Degrande et al, 14']
    - top pair production [Franzosi et al. 15']
    - single top production [Zhang 16']
    - $t\bar{t}Z$, $t\bar{t}\gamma$ [Bylund et al. 16']
    - $t\bar{t}h$ [Maltoni et al. 16']
    - four-fermion operators [$\bar{l}l\bar{q}q$ OK, $\bar{q}q\bar{q}q$ ongoing]

- QCD NLO matched to parton shower is then automatic. Progresses are made towards automatic EW NLO in the SM.

[Frixione et al. 14' ($t\bar{t}H$)]
[Frixione et al. 15' ($t\bar{t}Z/W$)]
[Pagani et al. 16' (photon-induced $t\bar{t}$)]

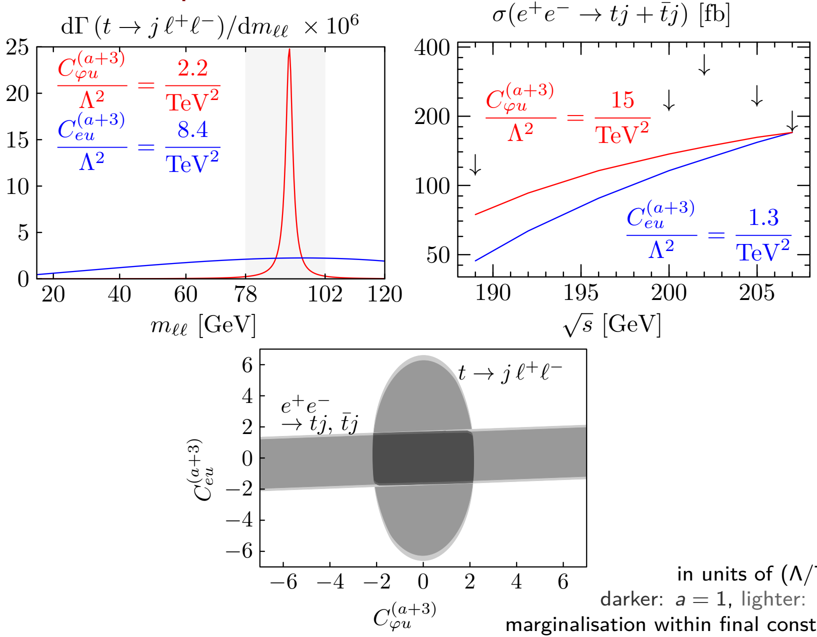
MadGraph for NLO QCD in the effective field theory

Example with four-fermion operators:



$1/\Lambda^{2,4}$ terms, unpolarised beams, α_s scale variation only

Four-fermion operators



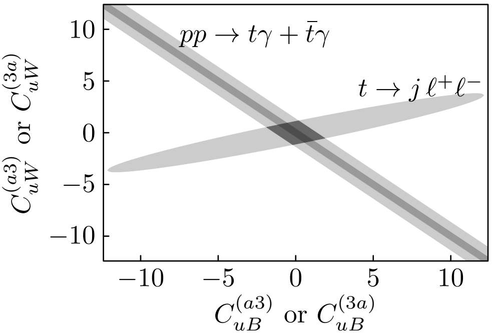
in units of $(\Lambda/\mathrm{TeV})^2$

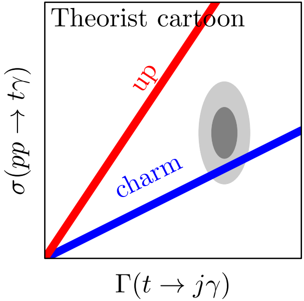
darker: $a = 1$, lighter: $a = 2$

marginalisation within final constraints

Production vs. decay

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





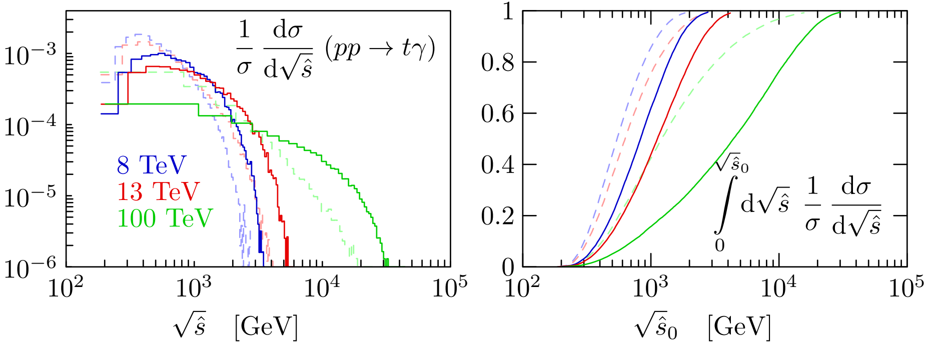
$C_{uA} \equiv C_{uW} + C_{uB}$
$C_{uZ} \equiv C_{uW}\ \cot\theta_W - C_{uB}\ \tan\theta_W$

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)



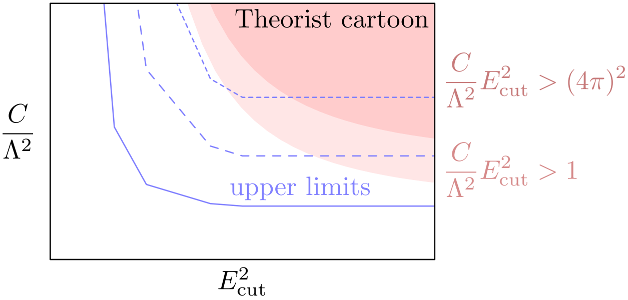
...until the EFT breaks down.

Validity of the EFT

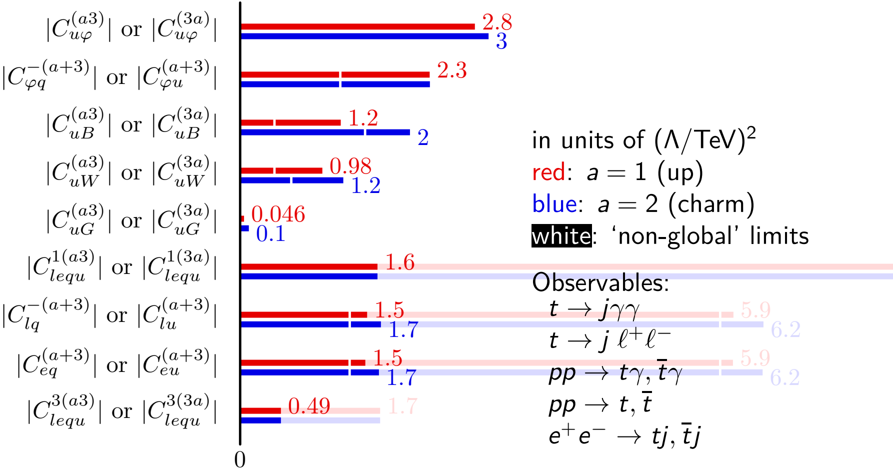
New-physics states should not be directly producible
$\equiv$ low-energy limit

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

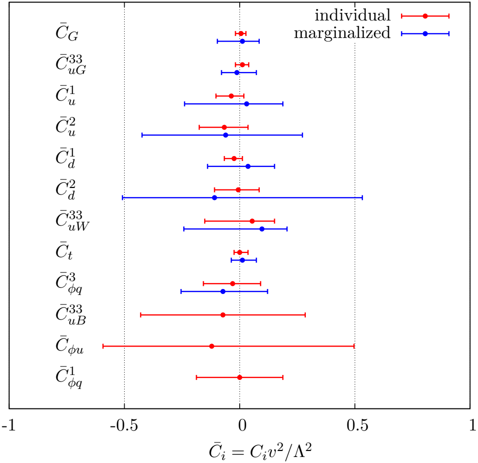


Possible experimental improvements:

- 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'

Towards a global top EFT analysis

- 195 observables (174 from differential distributions), 12 operators
- mainly from $t\bar{t}$, then single top, charge asymmetries, associated production, W helicity fraction in decay
- standard-model (N)NLO k-factors in each bin



[Buckley *et al.* 15']

[Buckley *et al.* 15']

Summary

The fully gauge-invariant EFT permits an accurate and model-independent interpretation of the data in terms of well-defined QFT parameters.

It accounts for correlations between observables arising from $SU(2)_L \times U(1)_Y$ gauge invariance.

It therefore allows, and actually requires, a global treatment.