Symmetry violations at the LHC

CP, flavour, ~~and baryon number~~

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Probing CP violation systematically in differential distributions

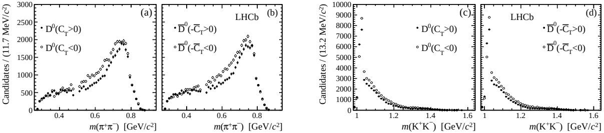
A global approach to top FCNCs

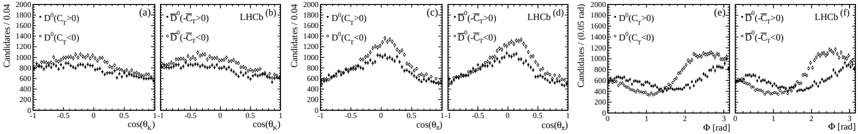
Multibody hadronic decays

1. Large statistics

$B^0 \to K^+K^-K^\pm\pi^\mp$	1700 candidates	[LHCb '14]
$B_s^0 \to K^+K^-K^+K^-$	4000	[LHCb '14]
$\boldsymbol{D^0 \to K^+K^-\pi^+\pi^-}$	**170 000**	**[LHCb '14]**
$B_s^0 \to K^+\pi^-K^-\pi^+$	700	[LHCb '15]
...		

2. Multidimensional phase space

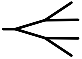
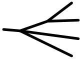
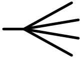




... on which *motion-reveral-odd* quantities can be defined.

Multibody hadronic decays

3. Rich variety of interfering contributions

	Intermediate states in $D^0 \to K^+K^-\pi^+\pi^-$	Br $/10^{-4}$
	$(\phi\rho^0)_S, \quad \phi \to K^+K^-, \quad \rho^0 \to \pi^+\pi^-$	9.3 ± 1.2
	D	0.83 ± 0.23
	$(K^{*0}\overline{K}^{*0})_S, \quad K^{*0} \to K^\pm\pi^\mp$	1.48 ± 0.30
	$\phi(\pi^+\pi^-)_S, \quad \phi \to K^+K^-$	2.50 ± 0.33
	$(K^-\pi^+)_P(K^+\pi^-)_S$	2.6 ± 0.5
	$K_1^+K^-, \quad K_1^+ \to K^{*0}\pi^+$	1.8 ± 0.5
	$K_1^-K^+, \quad K_1^- \to \overline{K}^{*0}\pi^-$	0.22 ± 0.12
	$K_1^+K^-, \quad K_1^+ \to \rho^0K^+$	1.14 ± 0.26
	$K_1^-K^+, \quad K_1^- \to \rho^0K^-$	1.46 ± 0.25
	$K^*(1410)^+K^-, \; K^*(1410)^+ \to K^{*0}\pi^+$	1.02 ± 0.26
	$K^*(1410)^-K^+, \; K^*(1410)^- \to \overline{K}^{*0}\pi^-$	1.14 ± 0.25

[CLEO '12]

$\Longrightarrow$ Opportunities for CP violation

Analysis techniques

Based on phenomenological parametrisations

- Full unbinned likelyhood fits
- Measurement of *expected* asymmetries

$\longrightarrow$ may miss *unexpected* manifestations of CP violation

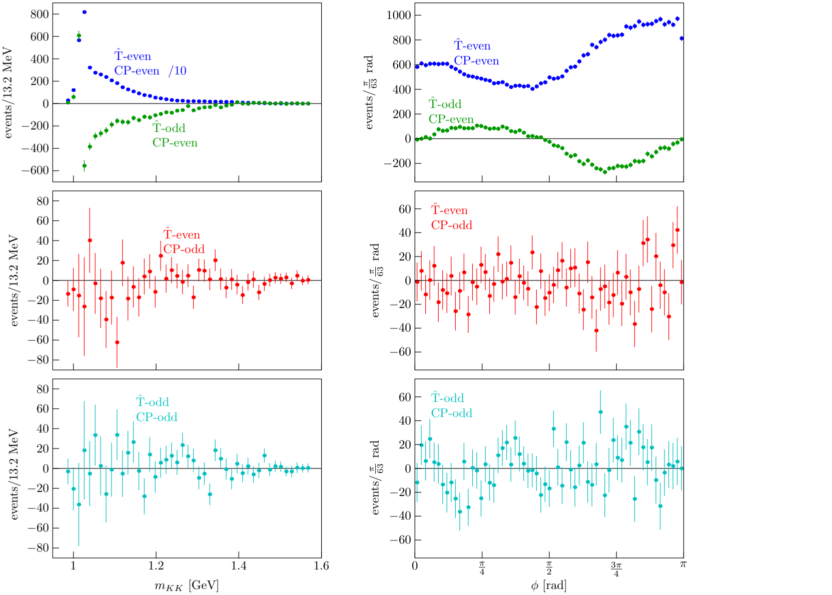
More systematic, relying some milder dynamical assumptions

- Phase-space binnings [LHCb '14]
- Decomposition in moments [Dighe et al '98, Beaujean et al '15, Gratrex et al '15]
- Series of asymmetries

i.e. integrated observables $\int \mathrm{d}\{\vec{p}_i\}\ \mathrm{f}(\{\vec{p}_i\})\ \left.\frac{\mathrm{d}\Gamma}{\mathrm{d}\{\vec{p}_i\}}\right|_{\text{CP-odd}}^{\hat{\text{T}}\text{-odd}}$

CP-violating distributions

$D^0 \to K^+K^-\pi^+\pi^-$



Probing CP violation systematically in differential distributions

High statistics allows for the accurate measurement of rich multidimensional differential distributions.

Symmetries characterize distributions measurable
- in the presence or absence of strong phases,
- in untagged samples.

Systematic procedures should be used to assess the departure from zero of CP-violating ones.

with Yuval Grossman (Cornell), [1508.03054]

Symmetry violations at the LHC

Probing CP violation systematically in differential distributions

A global approach to top FCNCs

Flavour-changing neutral currents

Vanishingly small in the SM

e.g. top decays: [Eilam et al, 91]

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

Flavour-changing neutral currents

Vanishingly small in the SM

e.g. top decays: [Eilam et al, 91]

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

*from production processes

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

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

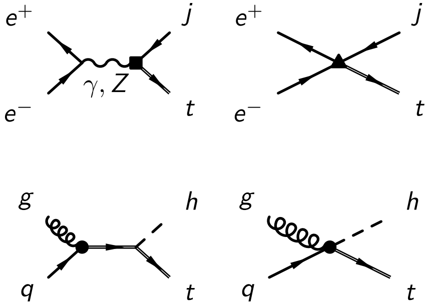
Tensor: $C_{lequ}^{3(a3)},\ C_{lequ}^{3(3a)}.$

Four-quark operators: ...

The broken-phase effective Lagrangian

Schematically:

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

Existing searches

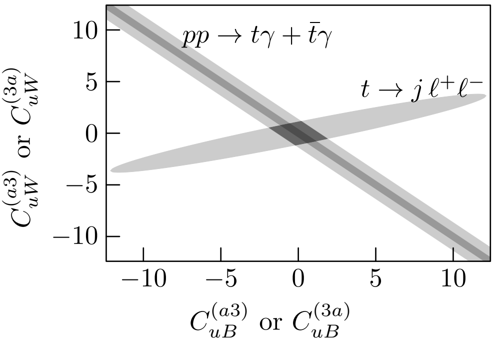
			tqg, T	$tqgh$ T	$tq\gamma$ T	tqZ V,T	$tq\ell\ell$ S,V,T	$tqqq$ S,V,T	tqh S
The broken-phase effective Lagrangian:			✓	✗	✓	✓,✓	✗	✗	✓
production	• $e^+e^- \to t\ j$	OPAL, DELPHI, ALEPH, L3			✓	✓,✗	✗		
production	$e^-p \to e^-t$	**H1**, ZEUS			✓	✗	✗		
production	• $p\overset{\scriptscriptstyle(-)}{p} \to t$	CDF, **ATLAS**	✓						
production	$p\overset{\scriptscriptstyle(-)}{p} \to t\ j$	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	• $t \to j\gamma\gamma$ ($\bar{b}b$, ℓ's)	**CMS**, ATLAS			✗				✓

One single contribution is often assumed, although:

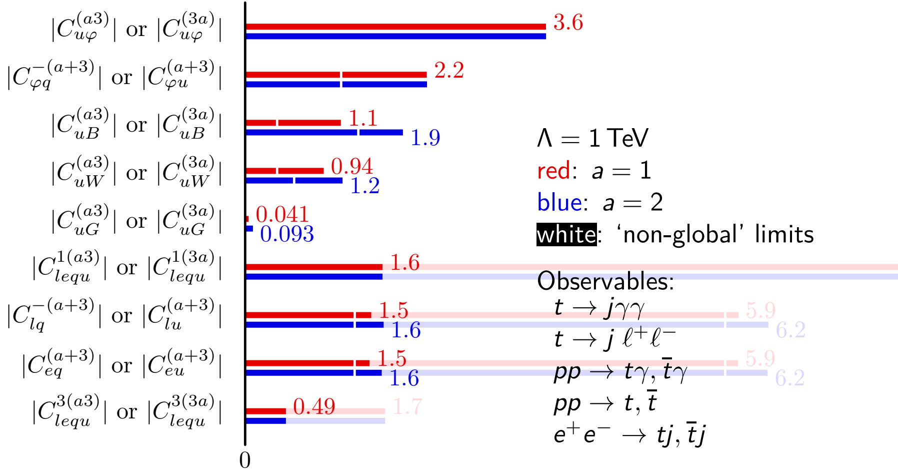
- NP could generate several operators at Λ.
- RG mixings (and fixed order corrections) would contaminate more of them at E.
- EOM, Fierz identities, etc. have converted some op. into combinations of others.

$\Rightarrow$ A consistent EFT treatment should include *all* operators of identical dimension!

A first global analysis at NLO in QCD



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 $pp \to t\gamma\gamma$
- Statistical combinations
- Angular distributions like 'helicity fractions'

A global approach to top FCNCs

High statistics allows for precision tests in the top sector.

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

Direct FCNC constraints can be set globaly.

Such an analysis could be combined with observables from other sectors, the B sector notably.

with Fabio Maltoni (Louvain) and Cen Zhang (BNL) [1412.7166]