Top couplings and new physics: theoretical overview and developments

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Top 2014, Cannes

Top quark couplings

✓ Top couplings based on EFT.

✗ NP models.

✓ Strategy for determining effective operators/couplings.

✓ EFT framework NLO accuracy.

✓ Flavor-conserving and flavor-changing couplings.

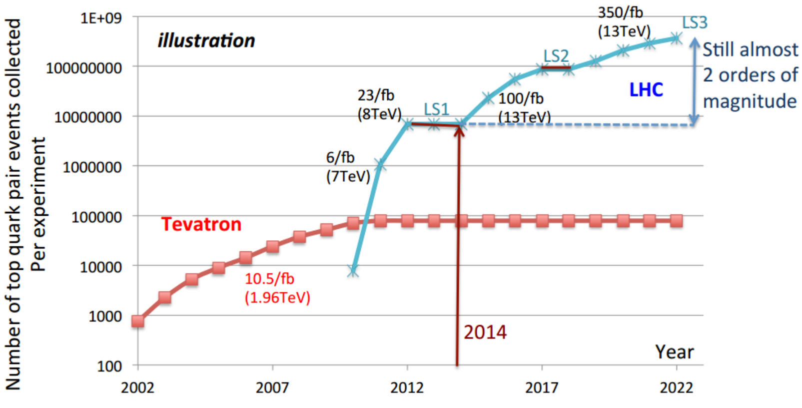
✗ CP-violation, DM couplings, B-number violation ...

Outline

Outline

Production at Tevatron and LHC

20 years for almost 6 orders of magnitude → the Top Quark era



(caveat: assumed 13 TeV collisions with a cross section of 800 pb)

Top precision era

With millions of top quarks,

- Many top-related parameters have been accurately measured
  - Top mass
  - $t\bar{t}$ and single t cross section
  - W helicity in top decay
  - FCNC at a level of Br $\sim 10^{-5}$
  - ...
- Provide / will provide information for us to determine top-quark couplings from *every possible* direction.

What's new in 2014

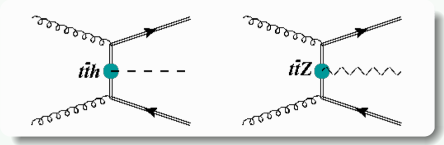
- EXP
  - Single t in tW channel — **1401.2942**
  - Search for tHj — **CMS-PAS-HIG-14-001**
  - $t\bar{t}H$ search — **1408.1682** **1409.3122**
  - Differential xsec for $t\bar{t}$ — **1407.0371**
  - ...
- TH
  - $t\bar{t}Z$ at NLO with spin correlation — **R. Rontsch and M. Schulze** 1404.1005
  - $t\bar{t}H$, NLO in EW — **S. Frixione et al.** 1407.0823
  - $t\bar{t}W$, NLO+NNLL — **H. T. Li et al.** 1409.1460
  - MG5_aMC@NLO, any SM at NLO+PS — **J. Alwall et al.** 1405.0301
  - ...

Top precision era

In the upcoming years we'll study top-quark couplings in

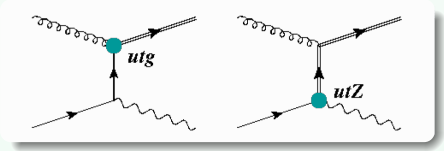
- More exclusive final state, $t\bar{t}H$, $t\bar{t}V$,...

Direct access to $t\bar{t}X$ couplings.



- Rare processes, e.g. $t \to qX$, $ug \to tX$

Push limits on FCNC couplings.



TH approach to couplings

From measurements to couplings: need a model-independent framework, which has to be consistent at NLO

- A complete TH framework for global analyses: EFT
- NLO corrections to the new couplings, or operators.
- Understand the mixing/contamination of the couplings due to higher-order.

EFT framework

Parametrize top-quark couplings with dimension-six operators in EFT
Instead of “couplings”, we prefer to talk about ”operators”

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i O_i}{\Lambda^2}$$

- A framework where radiative corrections can be systematically included.
- In principle, can go to any order of $(\alpha/\pi)^m \left(1/\Lambda^2\right)^n$.
- Other advantages such as preserving SM gauge symmetries and being able to remove redundant terms due to EOM. . .

Global fit at NLO

In EFT framework, global analyses for top couplings can be performed (like the Higgs fits), at NLO accuracy.

Keep in mind: in principle an EFT approach requires a complete basis of operators to be used. Should avoid "one operator at a time" strategy.

- *At LO neglecting some of them may still appear consistent. (a common mistake of using EFT)*
- *NLO counterterms and RG mixing effects clearly reveal the unnatural and inconsistent character of neglecting operators.*

$$\mathrm{d}C_i(\mu)/\,\mathrm{d}\ln\mu = \gamma_{ij}C_j(\mu)$$

- *For a consistent understanding of top couplings, one can only do a global fit at a fixed scale, i.e. including all relevant operators simultaneously.*

Global fit at NLO

For a global fit at NLO, we still need

- Understand mixing effects.
- NLO calculations including dim-6 operators.
- Simulation tools.
- Experiment results based on a global strategy.

R. Alonso et al.
1312.2014

For the first three, some progresses have been made in the FCNC sector.

Outline

In collaboration with
C. Degrande, G. Durieux, F. Maltoni and J. Wang

EFT for top FCNC

The FCNC sector is easier for a fit, because

- No interference with SM. Starts at $(C/\Lambda^2)^2$.
- Operator mixing structure is simple.

A top EFT for FCNC

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i O_i}{\Lambda^2}$$

requires a complete basis of flavor-changing operators to be used.

- Two-fermion operators, with one top-quark field one light-quark field.
- Four-fermion operators, with one top-quark field, one light-quark field and two leptons. *(Often neglected in FCNC searches)*

Top FCNC @ NLO

Operators

2-fermion operators

1. $(\bar{u}\gamma^{\mu}t)Z_{\mu}$

$$O_{\varphi Q}^{(3,1+3)} = i\left(\varphi^{\dagger}\tau^{I}D_{\mu}\varphi\right)\left(\bar{q}\gamma^{\mu}\tau^{I}Q\right)$$
$$O_{\varphi Q}^{(1,1+3)} = i\left(\varphi^{\dagger}D_{\mu}\varphi\right)(\bar{q}\gamma^{\mu}Q)$$
$$O_{\varphi u}^{(1+3)} = i\left(\varphi^{\dagger}D_{\mu}\varphi\right)(\bar{u}\gamma^{\mu}t)$$

2. $(\bar{u}\sigma^{\mu\nu}q_{\nu}t)V_{\mu}$, "weak dipole"

$$O_{uW}^{(13)} = (\bar{q}\sigma^{\mu\nu}\tau^{I}t)\tilde{\varphi}W_{\mu\nu}^{I}$$
$$O_{uB}^{(13)} = (\bar{q}\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu}$$

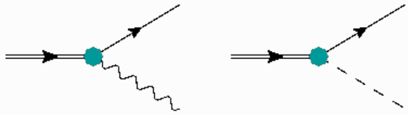
3. $(\bar{u}\sigma^{\mu\nu}q_{\nu}t)G_{\mu}$, "color dipole"

$$O_{uG}^{(13)} = (\bar{q}\sigma^{\mu\nu}T^{A}t)\tilde{\varphi}G_{\mu\nu}^{A}$$

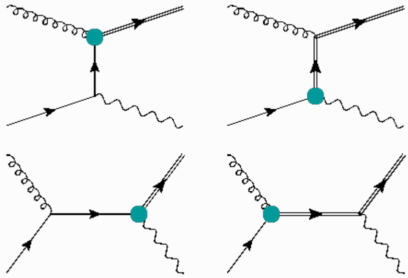
4. $\bar{u}th$, "Yukawa"

$$O_{u\varphi}^{(13)} = (\varphi^{\dagger}\varphi)(\bar{q}t)\tilde{\varphi}$$

FCNC t decay



FCNC t production



4-fermion operators

FCNC may be mediated by heavy particles.

- V-V

$$O_{lq}^{(1,1+3)} = (\bar{l}\gamma_\mu l)\,(\bar{q}\gamma^\mu Q)$$
$$O_{lq}^{(3,1+3)} = \left(\bar{l}\gamma_\mu\tau^I l\right)\left(\bar{q}\gamma^\mu\tau^I Q\right)$$
$$O_{lu}^{(1+3)} = (\bar{l}\gamma_\mu l)\,(\bar{u}\gamma^\mu t)$$
$$O_{qe}^{(1+3)} = (\bar{q}\gamma_\mu Q)\,(\bar{e}\gamma^\mu e)$$
$$O_{eu}^{(1+3)} = (\bar{e}\gamma_\mu e)\,(\bar{u}\gamma^\mu t)$$

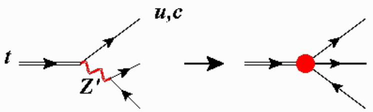
- S-S

$$O_{lequ}^{(1,13)} = (\bar{l}e)\,\varepsilon\,(\bar{q}t)$$
$$O_{lequ}^{(1,31)} = (\bar{l}e)\,\varepsilon\,(\bar{Q}u)$$

- T-T

$$O_{lequ}^{(3,13)} = (\bar{l}\sigma_{\mu\nu}e)\,\varepsilon\,(\bar{q}\sigma^{\mu\nu}t)$$
$$O_{lequ}^{(3,31)} = (\bar{l}\sigma_{\mu\nu}e)\,\varepsilon\,(\bar{Q}\sigma^{\mu\nu}u)$$

Top FCNC with a Z'

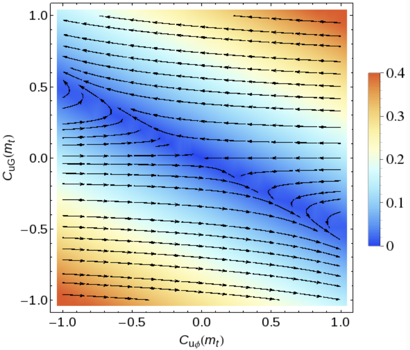


Top FCNC @ NLO

Mixings

Operator mixing in FCNC sector

Mixing between color-dipole and Yukawa



Operators

$$
\begin{aligned}
O_{uG}^{(13)} &= y_t g_s (\bar{q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu} \\
O_{uW}^{(13)} &= y_t g_W (\bar{q}\sigma^{\mu\nu} \tau^I t)\tilde{\varphi} W^I_{\mu\nu} \\
O_{uB}^{(13)} &= y_t g_Y (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu} \\
O_{u\varphi}^{(13)} &= -y_t^3 (\varphi^\dagger \varphi)(\bar{q}t)\tilde{\varphi}
\end{aligned}
$$

Anomalous dimension

$$
\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} & 0 \\ -2 & 0 & 0 & -1 \end{pmatrix}
$$

Scale corresponds to the change from m_t to 2 TeV.

Example:

At $\mu = 1$ TeV: $C_{uG}^{(13)} = 1$, $C_{u\varphi}^{(13)} = 0$ $\Rightarrow$ At $\mu = 173$ GeV: $C_{uG}^{(13)} = 0.98$, $C_{u\varphi}^{(13)} = 0.23$

Top FCNC @ NLO

NLO results for decays

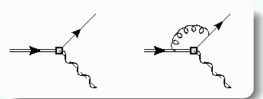
FCNC decay at NLO

- FCNC decay $t \to u(c) + X$
  Suppressed by GIM mechanism in the SM, $BR \approx 10^{-13} \sim 10^{-16}$
  but can be much larger in NP scenarios.

- NLO results in EFT are available for
  - $t \to u\gamma$, $t \to uZ$, $t \to ug$
  - $t \to uh$

J. Drobnak et al.
1007.2552
J.J. Zhang et al.
1004.0898
CZ and F. Maltoni
1305.7386

	$O_{\varphi q}^{(-,1+3)}$, $O_{\varphi u}^{(1+3)}$	$O_{uW}^{(13,31)}$	$O_{uB}^{(13,31)}$	$O_{u\varphi}^{(13,31)}$	$O_{uG}^{(13,31)}$
$t \to qZ$	✓	✓	✓		
$t \to q\gamma$		✓	✓		
$t \to qh$				✓	
$qg \to t$					✓



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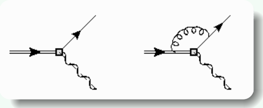
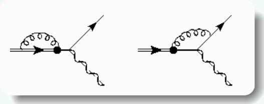
$t \to qZ$	✓	✓	✓		✓
$t \to q\gamma$		✓	✓		✓
$t \to qh$				✓	✓
$qg \to t$					✓





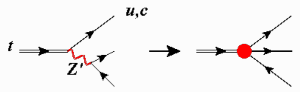
$$O_{uG}^{(13)} = g_s(\bar{q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G_{\mu\nu}^A$$

FCNC decay at NLO

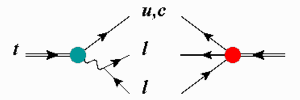
- FCNC decay $t \to u(c) + X$
  Suppressed by GIM mechanism in the SM, $BR \approx 10^{-13} \sim 10^{-16}$
  but can be much larger in NP scenarios.
- NLO results in EFT are available for
  - $t \to u\gamma$, $t \to uZ$, $t \to ug$
  - $t \to uh$
  - 4-fermion operators can contribute to $t \to ul^+l^-$ (and interfere with 2-f operators)
    Some four-fermion contributions can be as large as two-fermion ones
    (e.g. $(\bar{l}\sigma_{\mu\nu}e)\varepsilon(\bar{q}\sigma^{\mu\nu}t)$)

J. Drobnak et al. 1007.2552
J.J. Zhang et al. 1004.0898
CZ and F. Maltoni 1305.7386
C. Zhang 1404.1264

4-f operator from a Z'



4-f interfere with 2-f operator



Top FCNC @ NLO

NLO results for productions

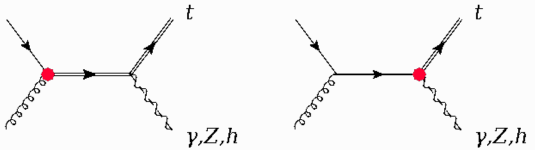
FCNC production at NLO

Single top production can bring new information on top FCNC.
In particular, here we are interested in $pp \to t\gamma$, $pp \to tZ$, $pp \to th$.
Discrimination of initial quark u/c due to PDF

- Two (or more) contributions appear at LO. (O_{uB} and O_{uG})
- At NLO in QCD O_{uG} mixes with other operators. Always has to be included.
- Previous NLO results
  - $ug \to t$, with tug vertex.
  - $ug \to tZ, t\gamma$, with tug and $tuZ/tu\gamma$ vertices.
  - $ug \to th$, with tuh (but no tug) vertex.

J. Gao et al. 0910.4349
Y. Zhang et al. 1101.5346
B. H. Li et al. 1103.5122
Y. Wang et al. 1208.2902

$pp \to tX$, $X = \gamma, Z, h$



FCNC production at NLO

Simulation tool

- Implementation of dim-6 FCNC (2-fermion) operators in aMC@NLO.
- Allows for automatic calculation at NLO in QCD, for any process.
- Events matched to shower at NLO accuracy.
  e.g. for $pp \to th$:

```
your_shell> ./bin/mg5
MG5_aMC> import model Top_FCNC
MG5_aMC> generate p p > t h [QCD]
MG5_aMC> output some_DIR
MG5_aMC> launch
```

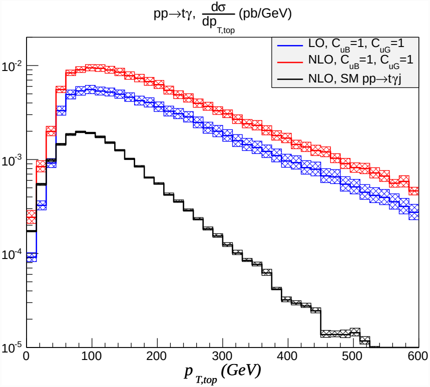
Event record file (or plots), after shower, will be found in

```
./some_DIR/Events/run_01/
```

FCNC production at NLO

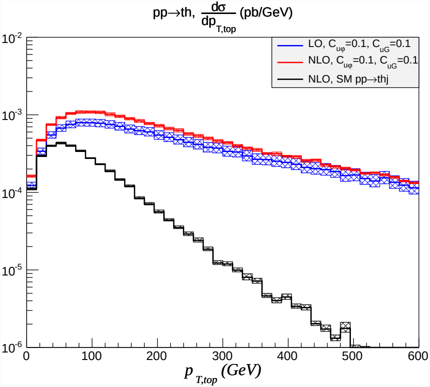
- Results for $pp \to t\gamma$ and $pp \to th$ at NLO+PS: p_T distribution for top (Λ=1 TeV)

Left: $pp \to t\gamma$



$pp \to t\gamma$ 13 TeV

Right: $pp \to th$



$pp \to th$ 13 TeV

Top FCNC @ NLO

Global fit

Global fit: operators

10 operators for *tcX* coupling

1. $(\bar{u}\gamma^{\mu}t)Z_{\mu}$

$$O_{\varphi Q}^{(-,2+3)} = \left[i\left(\varphi^{\dagger}\tau^{I}D_{\mu}\varphi\right)\left(\bar{q}\gamma^{\mu}\tau^{I}Q\right) - i\left(\varphi^{\dagger}D_{\mu}\varphi\right)\left(\bar{q}\gamma^{\mu}Q\right)\right]/2$$

$$O_{\varphi u}^{(2+3)} = i\left(\varphi^{\dagger}D_{\mu}\varphi\right)\left(\bar{u}\gamma^{\mu}t\right)$$

2. $(\bar{u}\sigma^{\mu\nu}q_{\nu}t)V_{\mu}$, "weak dipole"

$$O_{uW}^{(23)} = (\bar{q}\sigma^{\mu\nu}\tau^{I}t)\tilde{\varphi}W_{\mu\nu}^{I} \qquad O_{uW}^{(32)} = (\bar{Q}\sigma^{\mu\nu}\tau^{I}c)\tilde{\varphi}W_{\mu\nu}^{I}$$

$$O_{uB}^{(23)} = (\bar{q}\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu} \qquad O_{uB}^{(32)} = (\bar{Q}\sigma^{\mu\nu}c)\tilde{\varphi}B_{\mu\nu}$$

3. $(\bar{u}\sigma^{\mu\nu}q_{\nu}t)G_{\mu}$, "color dipole"

$$O_{uG}^{(23)} = (\bar{q}\sigma^{\mu\nu}T^{A}t)\tilde{\varphi}G_{\mu\nu}^{A} \qquad O_{uG}^{(32)} = (\bar{Q}\sigma^{\mu\nu}T^{A}c)\tilde{\varphi}G_{\mu\nu}^{A}$$

4. $\bar{u}th$, "Yukawa"

$$O_{u\varphi}^{(23)} = (\varphi^{\dagger}\varphi)(\bar{q}t)\tilde{\varphi} \qquad O_{u\varphi}^{(32)} = (\varphi^{\dagger}\varphi)(\bar{Q}c)\tilde{\varphi}$$

Global fit: observables

- $t \to qZ$:
  Br($t \to qZ$)<0.05% **CMS-TOP-12-037**
- $t \to qh$:
  Br($t \to ch$)<0.56% **CMS-PAS-HIG-13-034**
- $qg \to t$:
  Br($t \to ug$)<3.1×10^{-5}, Br($t \to cg$)<1.6×10^{-4} **ATLAS-CONF-2013-063**
- $qg \to t\gamma$:
  Br($t \to u\gamma$)<0.0161%, Br($t \to c\gamma$)<0.182%
  (assuming *tug* vanishes) **CMS-PAS-TOP-14-003**

Global fit: counting dof

In the case of FCNC, one observable can constrain several combinations of operator coefficients.

- For example in $t \to qZ$, the decay rate can be written as a sum of squares, corresponding to $t \to q_L Z_0$, $t \to q_R Z_0$, $t \to q_L Z_-$ and $t \to q_R Z_+$

At LO:

$$\Gamma_{t\to jZ} = \frac{\alpha m_t (1-x^2)^2}{8\Lambda^4 s_W^2 c_W^2}$$
$$\sum_{a=1,2} \Big\{ \left| \frac{1}{2x} C_{\varphi q}^{-(a+3)} - 2x \left(s_W^2 C_{uB}^{(a3)} - c_W^2 C_{uW}^{(a3)} \right) \right|^2 + \left| \frac{1}{2x} C_{\varphi u}^{(a+3)} - 2x \left(s_W^2 C_{uB}^{(3a)*} - c_W^2 C_{uW}^{(3a)*} \right) \right|^2$$
$$+2 \left| \frac{1}{2} C_{\varphi q}^{-(a+3)} + 2 \left(s_W^2 C_{uB}^{(a3)} - c_W^2 C_{uW}^{(a3)} \right) \right|^2$$
$$+2 \left| \frac{1}{2} C_{\varphi u}^{(a+3)} + 2 \left(s_W^2 C_{uB}^{(3a)*} - c_W^2 C_{uW}^{(3a)*} \right) \right|^2 \Big\},$$

Global fit: "contamination" at NLO

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- For example in $t \to qZ$, the decay rate can be written as a sum of squares, corresponding to $t \to q_L Z_0$, $t \to q_R Z_0$, $t \to q_L Z_-$ and $t \to q_R Z_+$

At NLO, $O_{uG}^{(a3,3a)}$ come in:

$$
\begin{aligned}
&\sum_{a=1,2} \Big\{ \left|0.40\ C_{\varphi q}^{-(a+3)} + 0.25\ C_{uB}^{(a3)} - 0.88\ C_{uW}^{(a3)} + 0.036\ C_{uG}^{(a3)}\right|^2 \\
&\quad + \left|0.40\ C_{\varphi u}^{(a+3)} + 0.25\ C_{uB}^{(3a)} - 0.88\ C_{uW}^{(3a)} - 0.021\ C_{uG}^{(3a)}\right|^2 \\
&+0.048 \left|0.92\ C_{\varphi q}^{-(a+3)} - 0.11\ C_{uB}^{(a3)} + 0.39\ C_{uW}^{(a3)} + 0.030\ C_{uG}^{(a3)}\right|^2 \\
&+0.048 \left|0.92\ C_{\varphi u}^{(a+3)} - 0.11\ C_{uB}^{(3a)} + 0.39\ C_{uW}^{(3a)} - 0.027\ C_{uG}^{(3a)}\right|^2 \Big\} \\
&\quad < 0.23 \left(\frac{\Lambda}{1\ \text{TeV}}\right)^4 .
\end{aligned}
$$

Global fit: counting dof

In the case of FCNC, one observable can constrain several combinations of operator coefficients.

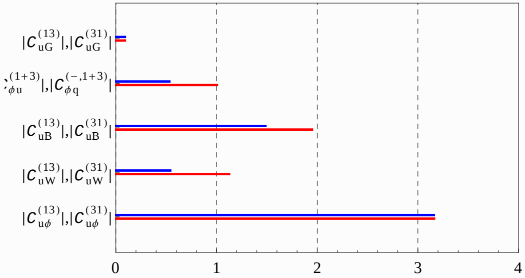
- For example in $t \to qZ$, the decay rate can be written as a sum of squares, corresponding to $t \to q_L Z_0$, $t \to q_R Z_0$, $t \to q_L Z_-$ and $t \to q_R Z_+$
- $4\ (t \to qZ) + 2\ (t \to ch) + 2\ (qg \to t) + 2\ (qg \to t\gamma) = 10$

Global limits

In the case of FCNC, one observable can constrain several combinations of operator coefficients.

- Result (with $\Lambda = 1$ TeV)

Global fit for FCNC operators



Blue: set other coefficients to zero. Red: float other coefficients.

Global limits

Four-fermion operators may be included, e.g.

- $O_{lq}^{(1,1+3)} = (\bar{l}\gamma_\mu l)\,(\bar{q}\gamma^\mu Q)$ (vector)
- $O_{lequ}^{(1,13)} = (\bar{l}e)\,\varepsilon\,(\bar{q}t)$ (scalar)
- $O_{lequ}^{(3,13)} = (\bar{l}\sigma_{\mu\nu}e)\,\varepsilon\,(\bar{q}\sigma^{\mu\nu}t)$ (tensor)

moreover include $e^+e^- \to tj$ at LEP2 in the fit. Results looks like

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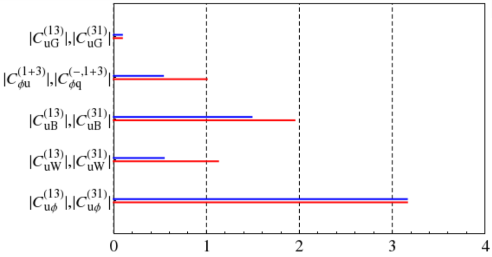
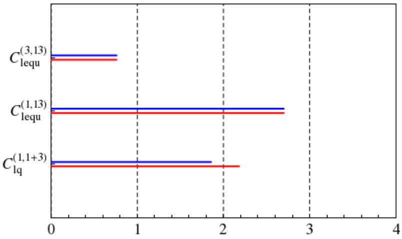
Global fit for FCNC operators





Blue: set other coefficients to zero. Red: float other coefficients.

FCNC Summary

- Complete EFT framework for FCNC
- Can be applies at NLO
- Mixing understood
- NLO predictions (almost) complete
- Exp results based on global strategy?

$\Rightarrow$ Global fit for FCNC couplings at NLO accuracy

Outline

EFT for flavor-conserving sector

- $tt\gamma/ttg$, EM/color dipole

$$O_{tB} = (\bar{Q}\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu} \qquad O_{tG} = (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}$$

- tbW
  - V/A

$$O^{(3)}_{\varphi Q} = i(\varphi^\dagger D_\mu \tau^I \varphi)(\bar{Q}\tau^I \gamma^\mu Q) \qquad O_{\varphi\varphi} = i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu b)$$

  - Weak dipole

$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu} \qquad O_{bW} = (\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu}$$

- ttZ
  - V/A

$$O^{(1)}_{\varphi Q} = i(\varphi^\dagger D_\mu \varphi)(\bar{Q}\gamma^\mu Q) \qquad O_{\varphi u} = i(\varphi^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu t)$$

  - Weak dipole O_{tW}
- ttH

$$O_{t\varphi} = (\varphi^\dagger \varphi)(\bar{Q}t)\tilde{\varphi}$$

Constraining top couplings

	O_{tG}	O_{tB}	O_{tW}	$O^{(3)}_{\varphi Q}$	$O^{(1)}_{\varphi Q}$	$O_{\varphi t}$	$O_{t\varphi}$
t-channel single t			✓	✓			
tW production	✓		✓	✓			
top decay			✓				
$t\bar{t}$	✓						
$t\bar{t}V$	✓	✓	✓	✓	✓	✓	
$t\bar{t}H$	✓						✓
$gg \to H$, $H \to \gamma\gamma$	✓						✓

- Dipole operators O_{tG}, O_{tB}, O_{tW}
- ttZ $O^{(3)}_{\varphi Q}$, $O^{(1)}_{\varphi Q}$, $O_{\varphi t}$
- ttH $O_{t\varphi}$ in Higgs fits.
- ...

A. Tonero and R. Rosenfeld
1404.2581

R. Rontsch and M.Schulze
1404.1005

Constraining top couplings

	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$
t-channel single t			✓	✓			
tW production	✓		✓	✓			
top decay			✓				
$t\bar{t}$	✓						
$t\bar{t}V$	✓	✓	✓	✓	✓	✓	
$t\bar{t}H$	✓						✓
$gg \to H$, $H \to \gamma\gamma$	✓						✓

However, there are still a lot more to do. . . We need

- A global analysis.
  Include all operators. Each data constrains a combination. Once we combine all data we constrain all couplings.

Constraining top couplings

	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_G	$O_{\varphi G}$	$O_{4\text{-f}}$
t-channel single t			✓	✓				✓		✓
tW production	✓		✓	✓						
top decay			✓							✓
$t\bar{t}$	✓							✓		✓
$t\bar{t}V$	✓	✓	✓	✓	✓	✓		✓		✓
$t\bar{t}H$	✓						✓	✓	✓	✓
$gg \to H$, $H \to \gamma\gamma$	✓						✓	✓	✓	

However, there are still a lot more to do. . . We need

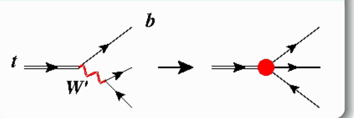
- A global analysis.
  More operators, in particular 4-fermion operators, should be included.

$$O_G = f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$$

$$O_{\varphi G} = \left(\varphi^\dagger \varphi\right) G_{\mu\nu}^A G^{A\mu\nu}$$

(mix with O_{tG} and $O_{t\varphi}$, see [C.Degrand et al, 1205.1065])

4-f operator from W'



Constraining top couplings

	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_G	$O_{\varphi G}$	$O_{4\text{-f}}$
t-channel single t			✓	✓				✓		✓
tW production	✓		✓	✓						
top decay			✓							✓
$t\bar{t}$	✓							✓		✓
$t\bar{t}V$	✓	✓	✓	✓	✓	✓		✓		✓
$t\bar{t}H$	✓						✓	✓	✓	✓
$gg \to H$, $H \to \gamma\gamma$	✓						✓	✓	✓	

However, there are still a lot more to do. . . We need

- A global analysis. In particular 4-fermion operators.
- NLO corrections, not only to SM but also to higher dim operators.
  - Only several operator are studied. $\sim 30 - 50\%$ for SM-like couplings.
  - QCD corrections to dim-6 FCNC operators $\sim 40 - 80\%$

Constraining top couplings

	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_G	$O_{\varphi G}$	$O_{4\text{-f}}$
t-channel single t	✓		✓	✓				✓		✓
tW production	✓		✓	✓				✓	✓	✓
top decay	✓		✓							✓
$t\bar{t}$	✓							✓	✓	✓
$t\bar{t}V$	✓	✓	✓	✓	✓	✓		✓	✓	✓
$t\bar{t}H$	✓						✓	✓	✓	✓
$gg \to H$, $H \to \gamma\gamma$	✓						✓	✓	✓	

However, there are still a lot more to do. . . We need

- A global analysis. In particular 4-fermion operators.
- NLO corrections, not only to SM but also to higher dim operators.
  - Only several operator are studied. $\sim 30-50\%$ for SM-like couplings.
  - QCD corrections to dim-6 FCNC operators $\sim 40-80\%$
  - Mixing/contamination due to higher order correction.

Constraining top couplings

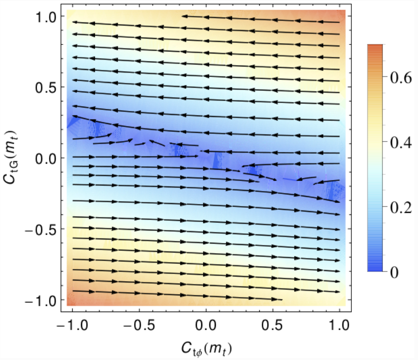
	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_G	$O_{\varphi G}$	$O_{4\text{-f}}$
t-channel single t	✓		✓	✓				✓		✓
tW production	✓		✓	✓				✓	✓	✓
top decay	✓		✓							✓
$t\bar{t}$	✓							✓	✓	✓
$t\bar{t}V$	✓	✓	✓	✓	✓	✓		✓	✓	✓
$t\bar{t}H$	✓						✓	✓	✓	✓
$gg \to H$, $H \to \gamma\gamma$	✓						✓	✓	✓	

However, there are still a lot more to do. . . We need

- A global analysis. In particular 4-fermion operators.
- NLO corrections, not only to SM but also to higher dim operators.
- Understand the RG mixing effect.

Operator Mixing between $t\bar{t}H$ and $t\bar{t}g$

Mixing between color-dipole and Yukawa



Operators

$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}$$
$$O_{tW} = y_t g_W(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$
$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu}$$
$$O_{t\varphi} = -y_t^3(\varphi^\dagger\varphi)(\bar{Q}t)\tilde{\varphi}$$

Anomalous dimension

$$\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} & 0 \\ -4 & 0 & 0 & -1 \end{pmatrix}$$

Scale corresponds to the change from m_t to 2 TeV.

Example:

At $\mu = 1$ TeV: $C_{tG} = 1$, $C_{t\varphi} = 0$ $\Rightarrow$ At $\mu = 173$ GeV: $C_{tG} = 0.98$, $C_{t\varphi} = 0.45$

Constraining top couplings

	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_G	$O_{\varphi G}$	$O_{4\text{-f}}$
t-channel single t	✓		✓	✓				✓		✓
tW production	✓		✓	✓				✓	✓	✓
top decay	✓		✓							✓
$t\bar{t}$	✓							✓	✓	✓
$t\bar{t}V$	✓	✓	✓	✓	✓	✓		✓	✓	✓
$t\bar{t}H$	✓						✓	✓	✓	✓
$gg \to H$, $H \to \gamma\gamma$	✓						✓	✓	✓	

However, there are still a lot more to do. . . We need

- A global analysis. In particular 4-fermion operators.
- NLO corrections, not only to SM but also to higher dim operators.
- Understand the RG mixing effect.
- Exp measurements based on a global approach.

Outline

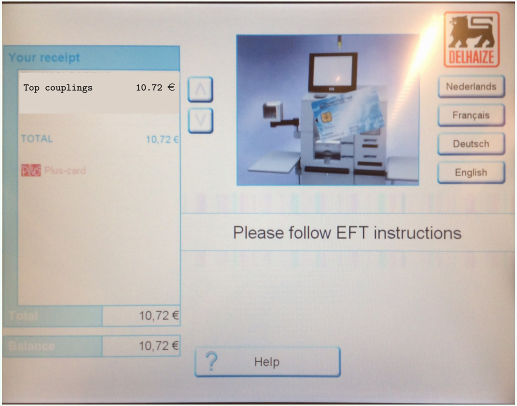
Summary

- TH framework for top couplings based on EFT, where predictions can be systematically improved, several measurements can be consistently combined, and useful information can be obtained by global fits.
- NLO corrections to higher dimensional operators are being studied. Some progresses have been made in top-quark FCNC sector. More to do in flavor-conserving sector.
- MC generator with full EFT framework at NLO in QCD will become available in future, providing a realistic tool needed for global analyses in the top sector.

It is time to seriously think about global analysis for top-quark couplings.

It is time to seriously think about global analysis for top-quark couplings.

and in order to do that...



Backups

Constraining top couplings

	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$
t-channel single t			✓	(✓)			
tW production	✓		✓	(✓)			
top decay			✓				
$t\bar{t}$	✓						
$t\bar{t}V$	✓	✓	✓	(✓)	(✓)	(✓)	
$t\bar{t}H$	(✓)						(✓)
$gg \to H$, $H \to \gamma\gamma$	(✓)						(✓)

- Dipole operators O_{tG}, O_{tB}, O_{tW}

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At 2σ CL

$$-0.4 < \bar{c}_{tB} < 0.4 \qquad -0.002 < \bar{c}_{tW} < 0.024 \qquad -0.007 < \bar{c}_{tG} < 0.002$$

$$\frac{C_{tB}}{\Lambda^2} = \frac{\bar{c}_{tB} g' y_t}{m_W^2} \qquad \frac{C_{tW}}{\Lambda^2} = \frac{\bar{c}_{tW} g y_t}{m_W^2} \qquad \frac{C_{tG}}{\Lambda^2} = \frac{\bar{c}_{tG} g_s y_t}{m_W^2}$$

(see also 1408.7063)

Constraining top couplings

	O_{tG}	O_{tB}	O_{tW}	$O^{(3)}_{\varphi Q}$	$O^{(1)}_{\varphi Q}$	$O_{\varphi t}$	$O_{t\varphi}$
t-channel single t			✓	✓			
tW production	✓		✓	✓			
top decay			✓				
$t\bar{t}$	✓						
$t\bar{t}V$	✓	✓	✓	✓	✓	✓	
$t\bar{t}H$	✓						✓
$gg \to H$, $H \to \gamma\gamma$	✓						✓

- ttZ $O^{(3)}_{\varphi Q}$, $O^{(1)}_{\varphi Q}$, $O_{\varphi t}$

R. Rontsch and M.Schulze
1404.1005

$$-0.5 < \frac{v^2}{\Lambda^2} C^{(3)}_{\varphi Q} < 0.68 \qquad C^{(1)}_{\varphi Q} = -C^{(3)}_{\varphi Q}$$

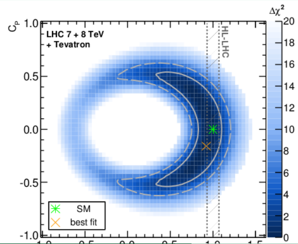
$$-0.82 < \frac{v^2}{\Lambda^2} C_{\varphi t} < 1.59$$

Constraining top couplings

	O_{tG}	O_{tB}	O_{tW}	$O^{(3)}_{\varphi Q}$	$O^{(1)}_{\varphi Q}$	$O_{\varphi t}$	$O_{t\varphi}$
t-channel single t			✓	✓			
tW production	✓		✓	✓			
top decay			✓				
$t\bar{t}$	✓						
$t\bar{t}V$	✓	✓	✓	✓	✓	✓	
$t\bar{t}H$	✓						✓
$gg \to H$, $H \to \gamma\gamma$	✓						✓

- ttH $O_{t\varphi}$ $\quad\left(C_S = \frac{\mathrm{Re}C_{t\varphi} v^2}{2\Lambda^2 y_t},\ C_P = \frac{\mathrm{Im}C_{t\varphi} v^2}{2\Lambda^2 y_t}\right)$

A. Kobakhidze et al.
1406.1961



and from direct measurement
$-1.3 < C_S < 8.0$

1409.3122

Indirect bounds...

Indirect bounds on top couplings from precision measurements also provide useful information.

- Weak operators from precision EW test.
- $O_{\varphi Q}^{(3)}$ and $O_{\varphi t}$ from T, δg_b^L and $B_s \to \mu^+\mu^-$.
- Wtb vertex from $B_{d,s} - \bar{B}_{d,s}$, $B \to X_s l^+ l^-$, $B \to X_s \gamma$.
- ttH from EDM.
- RG-induced bounds

But most results have some kind of "ambiguity"

Indirect bounds from loops

Bounds from loop are sensitive to TH assumptions
Typically, for a observable X, at loop level a "tree-level" operator absorbs divergence from the "loop-level" operator

$$X \sim C_{tree} + C_{loop}\frac{\alpha}{\pi}\left(\frac{1}{\varepsilon} + \log\frac{E}{\mu} + finite\right)$$

In $\overline{MS}$,

$$\text{at } \mu \sim E \quad X = C_{tree}(\mu) + C_{loop}\frac{\alpha}{\pi}\left(\log\frac{E}{\mu} + finite\right)$$

$$\text{at } \mu \sim \Lambda \quad X = C_{tree}(\Lambda) + C_{loop}\frac{\alpha}{\pi}\left(\log\frac{E}{\Lambda} + finite\right)$$

To get bound, assume "no unnatural cancellation between C_{tree} and C_{loop}"

$$C_{tree}(\mu) = 0 \Rightarrow C_{loop} \sim X/\left(\frac{\alpha}{\pi} finite\right)$$

$$C_{tree}(\Lambda) = 0 \Rightarrow C_{loop} \sim X/\left(\frac{\alpha}{\pi}\log\frac{E}{\Lambda}\right) \qquad \text{RG-induced bound}$$

Still, in principle ambiguities can be avoided in a global fit.

Global fit at NLO

- While an EFT description in principle requires a complete basis of operators to be used, at LO neglecting some of them may appear consistent. (a common mistake of using EFT)
- NLO counterterms and RG mixing effects clearly reveal the unnatural and inconsistent character of neglecting operators.
- For a consistent understanding of top couplings, one should do a global fit at a fixed scale, i.e. constrain all operators simultaneously, for at least two reasons:

Naturalness Even though one can make a specific (arbitrary) choice of operator coefficients high scales (where one can imagine a full theory to live), when evolved to lower scales many operators become active due to operator mixing.

$\Longrightarrow$ *Should include every operator that might contribute. e.g. both vector and tensor coupling for ttZ, 4-fermion operator, etc.*

Renomalizability If one neglects any operator that is renormalized by other operators, then one can not get a finite result, because of missing counterterms.

$\Longrightarrow$ *At least, need to include enough operators to make a NLO calculation renormalizable.*

FCNC mixing

$$
\begin{aligned}
O_{uG}^{(13)} &= y_t g_s (\bar{q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu} \\
O_{uW}^{(13)} &= y_t g_W (\bar{q}\sigma^{\mu\nu} \tau^I t)\tilde{\varphi} W^I_{\mu\nu} \\
O_{uB}^{(13)} &= y_t g_Y (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu} \\
O_{u\varphi}^{(13)} &= -y_t^3 (\varphi^\dagger \varphi)(\bar{q}t)\tilde{\varphi}
\end{aligned}
$$

$$
\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} & 0 \\ -2 & 0 & 0 & -1 \end{pmatrix}
$$

same for:

$$
\begin{aligned}
O_{uG}^{(31)} &= y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A u)\tilde{\varphi} G^A_{\mu\nu} \\
O_{uW}^{(31)} &= y_t g_W (\bar{Q}\sigma^{\mu\nu} \tau^I u)\tilde{\varphi} W^I_{\mu\nu} \\
O_{uB}^{(31)} &= y_t g_Y (\bar{Q}\sigma^{\mu\nu} u)\tilde{\varphi} B_{\mu\nu} \\
O_{u\varphi}^{(31)} &= -y_t^3 (\varphi^\dagger \varphi)(\bar{Q}u)\tilde{\varphi}
\end{aligned}
$$

$$
\begin{aligned}
O_{dG}^{(13)} &= y_t g_s (\bar{q}\sigma^{\mu\nu} T^A b)\varphi G^A_{\mu\nu} \\
O_{dW}^{(13)} &= y_t g_W (\bar{q}\sigma^{\mu\nu} \tau^I b)\varphi W^I_{\mu\nu} \\
O_{dB}^{(13)} &= y_t g_Y (\bar{q}\sigma^{\mu\nu} b)\varphi B_{\mu\nu} \\
O_{d\varphi}^{(13)} &= -y_t^3 (\varphi^\dagger \varphi)(\bar{q}b)\varphi
\end{aligned}
$$

$$
\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ -\frac{1}{9} & 0 & \frac{1}{3} & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}
$$

same for:

$$
\begin{aligned}
O_{dG}^{(31)} &= y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A d)\varphi G^A_{\mu\nu} \\
O_{dW}^{(31)} &= y_t g_W (\bar{Q}\sigma^{\mu\nu} \tau^I d)\varphi W^I_{\mu\nu} \\
O_{dB}^{(31)} &= y_t g_Y (\bar{Q}\sigma^{\mu\nu} d)\varphi B_{\mu\nu} \\
O_{d\varphi}^{(31)} &= -y_t^3 (\varphi^\dagger \varphi)(\bar{Q}d)\varphi
\end{aligned}
$$

Some numerical results for $t \to ull$

Results for several typical (2-f and 4-f) operators, for $t \to ull$, assuming $C_i/\Lambda^2 = 1\ \mathrm{TeV}^{-2}$.
(In total, 8 two-fermion + 8 four-fermion operators.)

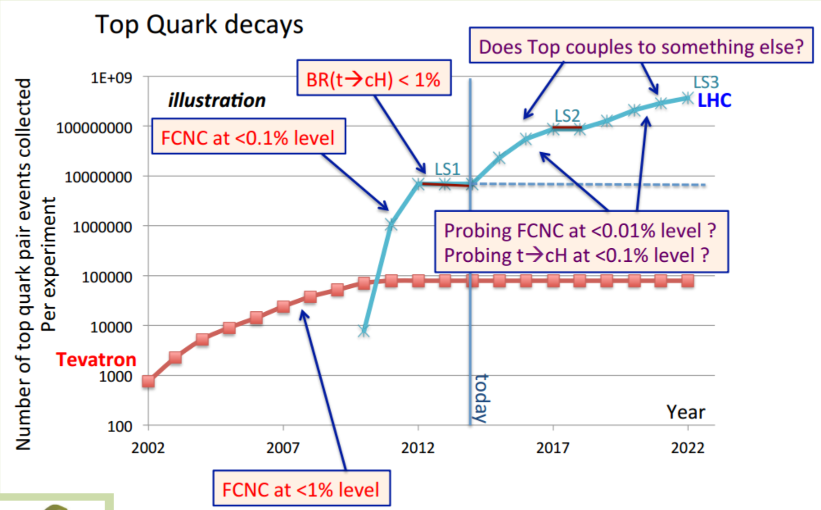
- 2-f and V-V (4-f) operators

$Unit: GeV$	$\Re\left(C_{\varphi q}^{(1,1+3)}\right)$	$\Re\left(C_{uW}^{(13)}\right)$	$\Re\left(C_{uG}^{(13)}\right)$	$\Re\left(C_{lq}^{(1,1+3)}\right)$
$\Re\left(C_{\varphi q}^{(1,1+3)}\right)$	$\underset{-8\%}{1.9 \times 10^{-5}}$	$\underset{-8\%}{-6.2 \times 10^{-5}}$	$\underset{---}{2.9 \times 10^{-6}}$	$\underset{-12\%}{-3.5 \times 10^{-7}}$
$\Re\left(C_{uW}^{(13)}\right)$		$\underset{-9\%}{7.6 \times 10^{-5}}$	$\underset{---}{-6.1 \times 10^{-6}}$	$\underset{-7\%}{-3.3 \times 10^{-6}}$
$\Re\left(C_{uG}^{(13)}\right)$			$\underset{---}{6.8 \times 10^{-8}}$	$\underset{---}{2.6 \times 10^{-7}}$
$\Re\left(C_{lq}^{(1,1+3)}\right)$				$\underset{-8\%}{2.9 \times 10^{-6}}$

- S-S and T-T (4-f) operators

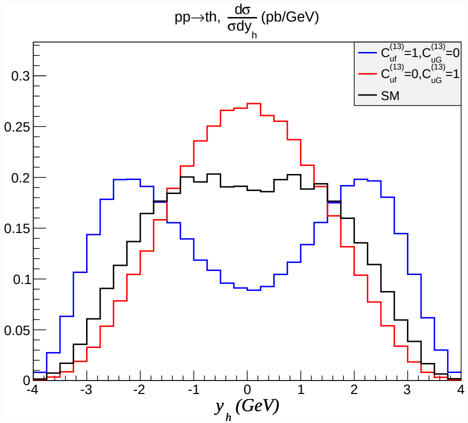
$Unit: GeV$	$\Re\left(C_{lequ}^{(1,13)}\right)$	$\Re\left(C_{lequ}^{(3,13)}\right)$
$\Re\left(C_{lequ}^{(1,13)}\right)$	$\underset{1\%}{8.2 \times 10^{-7}}$	$\underset{---}{0.}$
$\Re\left(C_{lequ}^{(3,13)}\right)$		$\underset{-8\%}{3.5 \times 10^{-5}}$

The status of Top Quark Physics

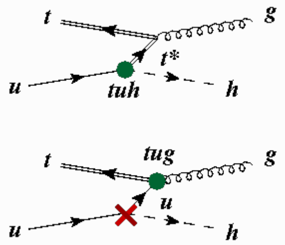


FCNC production at NLO

- Higgs rapidity distribution from O_{uG} and $O_{u\varphi}$ in $pp \to th$



$pp \to th$ 13 TeV



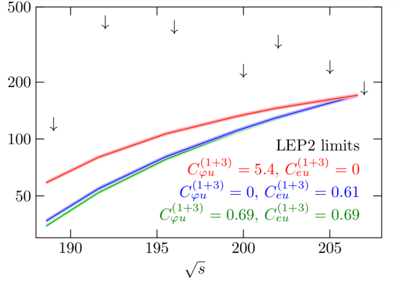
four-fermion operators at lep2

four-fermion operators in $e^+e^- \to t\bar{q}$

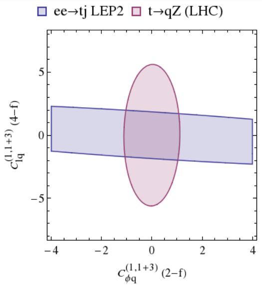
- consider for example 2-f operator $o_{\varphi u}^{(1+3)} = i\left(\varphi^\dagger d_\mu \varphi\right)\left(\bar{u}\gamma^\mu t\right)$ and 4-f vector operator $o_{eu}^{(1+3)} = \left(\bar{e}\gamma_\mu e\right)\left(\bar{u}\gamma^\mu t\right)$ in lep2

nlo cross sections available via mg5_amc@nlo

$e^+e^- \to t\bar{q}$ at lep2 (preliminary)

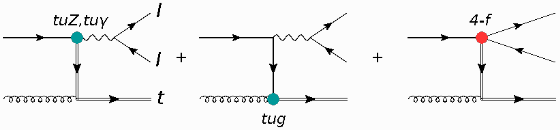


combined limits from lep2 and lhc

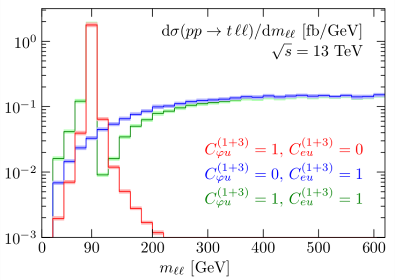


four-fermion operators in $pp \to tll$

$pp \to tll$ ($pp \to tz$)



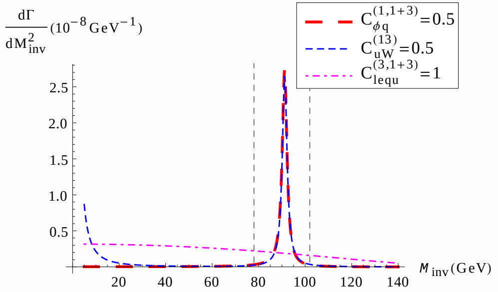
$pp \to tll$ 13 tev, nlo+ps (preliminary)



lepton inv. mass distribution in $pp \to tll$, from 2-f operator $o^{(1+3)}_{\varphi u}$ only, from 4-f operator o_{eu} only, and from their interference.

Four-fermion operators in $t \to qZ$

Lepton pair inv. mass distribution in $t \to ull$:



- 2-f operators ($O_{\varphi q}, O_{uW} \ldots$), $t \to uZ$, $Z \to ll$.
  $\Rightarrow$ peak at Z mass.
- 4-f operators ($O_{lequ}, \ldots$), $t \to ull$.
  $\Rightarrow$ continuous spectrum.
  However, 4-f contribution is not negligible, even with cuts on M_{ll}.

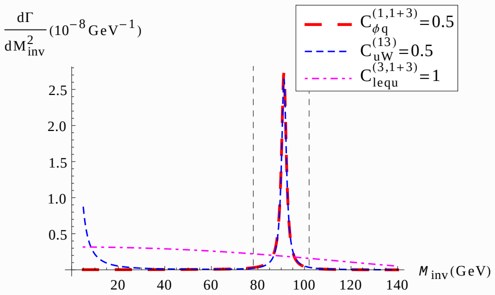
On-shell cut: $M_{ll} \in [78, 102]$ GeV (taken from 1312.4194)

$$\Gamma_{\rm on} = \left(7.0|C^{(13)}_{uW}|^2 + 7.3|C^{(1,1+3)}_{\varphi q}|^2 + 0.8|C^{(3,13)}_{lequ}|^2\right) \times 10^{-5}\ \mathrm{GeV}$$

$$\Rightarrow \delta C^{(13)}_{uW} : \delta C^{(1,1+3)}_{\varphi q} : \delta C^{(3,13)}_{lequ} \approx 1 : 1 : 3$$

Four-fermion operators in $t \to qZ$

Lepton pair inv. mass distribution in $t \to ull$:



- 2-f operators ($O_{\varphi q}, O_{uW} \ldots$), $t \to uZ$, $Z \to ll$. $\Rightarrow$ peak at Z mass.
- 4-f operators ($O_{lequ}, \ldots$), $t \to ull$. $\Rightarrow$ continuous spectrum. However, 4-f contribution is not negligible, even with cuts on M_{ll}.

Alternatively, could also look at off-shell region: $M_{ll} \in [15, 78] \cup [102, \infty]$ GeV

$$\Gamma_{\mathrm{off}} = \left(0.6|C^{(13)}_{uW}|^2 + 0.4|C^{(1,1+3)}_{\varphi q}|^2 + 2.7|C^{(3,13)}_{lequ}|^2\right) \times 10^{-5}\,\mathrm{GeV}$$

4-fermion operator has a larger contribution. Might get improved limit on 4-fermion operator due to less Drell-Yan background.

Four-fermion operators in $t \to qZ$

One can constrain

- 2-f operator
  (e.g. $O_{\varphi q}^{(1,1+3)} = i\left(\varphi^\dagger D_\mu \varphi\right)\left(\bar{q}\gamma^\mu Q\right)$)
- 4-f operator
  (e.g. $O_{lequ}^{(1,13)} = \left(\bar{l}\sigma_{\mu\nu} e\right)\varepsilon\left(\bar{q}\sigma^{\mu\nu} t\right)$)

simultaneously, by looking at both on-shell and off-shell region of M_{ll}

Limit from $t \to qZ$