Effective Approach to Top Quark Decay and FCNC Processes at NLO

Cen Zhang

Université Catholique de Louvain

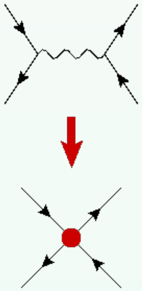
Centre for Cosmology, Particle Physics and Phenomenology

Based on several ongoing works
with C. Degrande, G. Durieux, F. Maltoni and J. Wang

22 July 2014
Beach 2014

Effective Field Theory:

- Integrate out heavy states at high energy scales.
- Calculate using resulting effective operators at low energy scales.
- Good for energy scale separation.



Effective Field Theory is playing a more and more important role in top quark physics, because

- No new particles have been discovered. Limits on NP scales have been pushed higher and higher.
- Top quark physics has evolved into precision physics.

$\Rightarrow$ Top quark physics is becoming more and more like flavor physics.

Effective Field Theory is playing a more and more important role in top quark physics, because

- No new particles have been discovered. Limits on NP scales have been pushed higher and higher.
- Top quark physics has evolved into precision physics.

$\Rightarrow$ Top quark physics is becoming more and more like flavor physics.

Outline

Outline

Two approaches to NP

Roughly, there are two approaches to NP:

- Directly, look for new particles at high energy.
  - Top quark physics (used to) fall in this category.
    e.g. resonances in $t\bar{t}$, stop and t' production, $H^{\dagger} \to t\bar{b}$, . . .
  - However, exclusion limit has been placed, up to several TeV.
- Indirectly, probe NP through virtual effects, in precision measurements.
  - Need effective theories.
  - Flavor physics falls in this category.
  - As the top quark physics develops into precision physics, and limits on NP being pushed higher and higher, now top quark physics also belongs to this category.
    - *W helicity fractions in top quark decay, top quark FCNC processes, . . .*

Two approaches to NP

Roughly, there are two approaches to NP:

- Directly, look for new particles at high energy.
  - Top quark physics (used to) fall in this category.
    e.g. resonances in $t\bar{t}$, stop and t' production, $H^\dagger \to t\bar{b}$, ...
  - However, exclusion limit has been placed, up to several TeV.
- Indirectly, probe NP through virtual effects, in precision measurements.
  - Need effective theories.
  - Flavor physics falls in this category.
  - As the top quark physics develops into precision physics, and limits on NP being pushed higher and higher, now top quark physics also belongs to this category.
    - *W helicity fractions in top quark decay, top quark FCNC processes, ...*

Two approaches to NP

Roughly, there are two approaches to NP:

- Directly, look for new particles at high energy.
  - Top quark physics (used to) fall in this category.
    e.g. resonances in $t\bar{t}$, stop and t' production, $H^\dagger \to t\bar{b}$, ...
  - However, exclusion limit has been placed, up to several TeV.
- Indirectly, probe NP through virtual effects, in precision measurements.
  - Need effective theories.
  - Flavor physics falls in this category.
  - As the top quark physics develops into precision physics, and limits on NP being pushed higher and higher, now top quark physics also belongs to this category.
    - *W helicity fractions in top quark decay, top quark FCNC processes,...*

Effective field theory

EFT calculation in 3 steps

1. Integrating out heavy states, i.e. matching. Obtain effective theory with only light degrees of freedom.
2. Using RG equations to bring the theory down to lower scale.
3. Low energy calculation.

Each step can be improved systematically

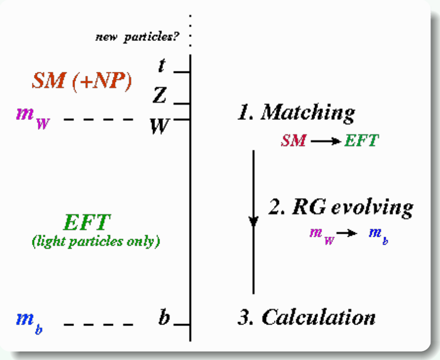
Effective field theory

EFT calculation in 3 steps

1. Integrating out heavy states, i.e. matching. Obtain effective theory with only light degrees of freedom.
2. Using RG equations to bring the theory down to lower scale.
3. Low energy calculation.

Each step can be improved systematically

EFT for *b*



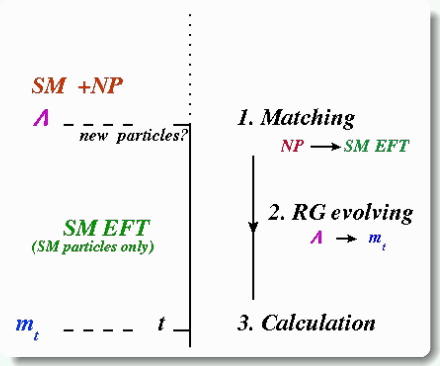
Effective field theory

EFT calculation in 3 steps

1. Integrating out heavy states, i.e. matching. Obtain effective theory with only light degrees of freedom.
2. Using RG equations to bring the theory down to lower scale.
3. Low energy calculation.

Each step can be improved systematically

EFT for t



Effective field theory, anomalous dimension

- RG equations:

one-loop anomalous dimension has been completed recently, for dim-6 operators.

R. Alonso et al. 1312.2014

- All coupling orders, $g^2/16\pi^2$, $y^2/16\pi^2$, $\lambda/16\pi^2$, are considered.
- 2499×2499 anomalous dimension matrix.

Effective filed theory, NLO results

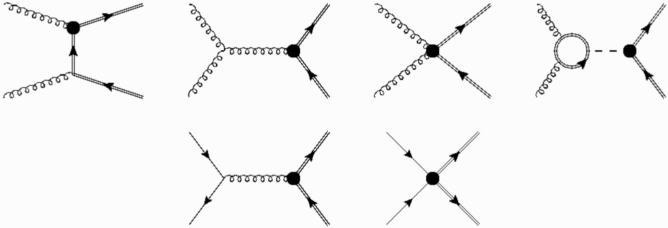
- NLO results (at top mass scale):

NLO in QCD available for

- Top quark decays.
- Some production processes: $t\bar{t}$ asymmetries, single top, etc.
- Event generator at NLO for top quark FCNC processes will be available soon.

Effective operators in $t\bar{t}$ production

$pp \to t\bar{t}$ at LO:



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

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

$$O^{(1,3)}_{qQ} = \left(\bar{q}\gamma_\mu \tau^I q\right) \left(\bar{Q}\gamma^\mu \tau^I Q\right)$$

and more 4-fermion operators. . .

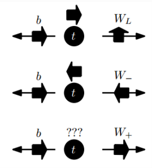
Outline

New physics in top-quark decays

The large sample of top quark produced at the Tevatron and the LHC allows to measure or set stringent limits on

- Main channel $t \to bW$, focusing on *Wtb* vertex.
- Flavor changing rare decay $t \to qX$, i.e. via top FCNC.
- $t \to H^+b$, $t \to W^*bh$, $t \to \text{invis.}, \ldots$

$t \to bW$



- Main decay channel is $t \to bW$.

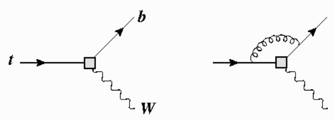
Key observable: W-helicity fraction.
In the SM, $F_+ : F_0 : F_- \sim 0 : 0.7 : 0.3$

  - SM predictions available at NLO in QCD & EW, and NNLO in QCD.

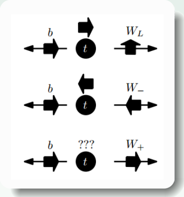
- The helicity fractions will be modified by dim-6 operators.
  - Operators involving *Wtb* vertex are computed at NLO in QCD.

J. Drobnak et al.
1010.2402

$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t_R)\tilde{\varphi}W^I_{\mu\nu}$ (and more)



$t \to bW$



- Main decay channel is $t \to bW$.

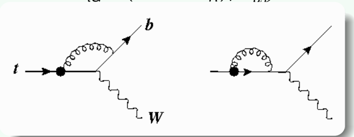
  Key observable: W-helicity fraction.
  In the SM, $F_+ : F_0 : F_- \sim 0 : 0.7 : 0.3$

  - SM predictions available at NLO in QCD & EW, and NNLO in QCD.

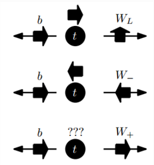
- The helicity fractions will be modified by dim-6 operators.
  - Operators involving *Wtb* vertex are computed at NLO in QCD.
  - Top-color dipole operator, i.e. *gtt* vertex, contributes only at NLO.

J. Drobnak et al.
1010.2402

$$O_{tG} = (\bar{Q}\sigma^{\mu\nu}T^A t_R)\tilde{\varphi}G^I_{\mu\nu}$$



$t \to bW$



- Main decay channel is $t \to bW$.

Key observable: W-helicity fraction.
In the SM, $F_+ : F_0 : F_- \sim 0 : 0.7 : 0.3$

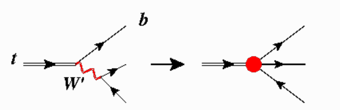
  - SM predictions available at NLO in QCD & EW, and NNLO in QCD.

- The helicity fractions will be modified by dim-6 operators.
  - Operators involving *Wtb* vertex are computed at NLO in QCD.
  - Top-color dipole operator, i.e. *gtt* vertex, contributes only at NLO.
  - 4-fermion operators are also considered at NLO. (May change F_+.)

J. Drobnak et al. 1010.2402

C. Zhang 1404.1264

$$O_{qQ}^{(1,3)} = \left(\bar{q}\gamma_\mu \tau^I q\right)\left(\bar{Q}\gamma^\mu \tau^I Q\right)$$



$t \to bW$

- W helicity fractions are measured at Tevatron and LHC. Currently

CMS Collaboration
1308.3879

$$F_0 = 0.682 \pm 0.030(\text{stat.}) \pm 0.033(\text{syst.})$$
$$F_L = 0.310 \pm 0.022(\text{stat.}) \pm 0.022(\text{syst.})$$

(with -0.95 correlation between F_0 and F_L)

- One can constrain some two-fermion operators using these results. For example, for O_{tW} (setting other operator coefficients to zero)

$$\frac{C_{tW}}{\Lambda^2} = -0.08 \pm 0.55\,\text{TeV}^{-2}$$

- However, one should keep in mind that four-fermion operators can affect the results, and they are not taken into account in the current measurements.

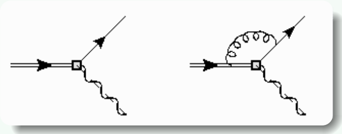
FCNC top decay

- 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
  - $t \to u\gamma$, $t \to uZ$, $t \to ug$
  - $t \to uh$

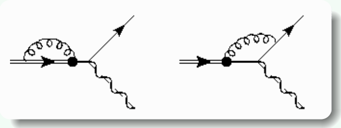
J. Drobnak et al. 1007.2552
J.J. Zhang et al. 1004.0898
CZ and F. Maltoni 1305.7386

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

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



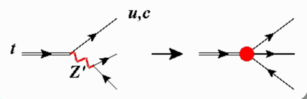
$$O_{uG}^{(13)} = g_s(\bar{q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G_{\mu\nu}^A$$



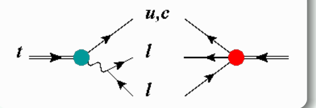
FCNC top decay

- 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
  - $t \to u\gamma$, $t \to uZ$, $t \to ug$ — **J. Drobnak et al.** 1007.2552; **J.J. Zhang et al.** 1004.0898
  - $t \to uh$ — **CZ and F. Maltoni** 1305.7386
  - 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. $(\bar{l}\sigma_{\mu\nu}e)\varepsilon(\bar{q}\sigma^{\mu\nu}t)$) — **C. Zhang** 1404.1264

4-f operator from a Z'



4-f interfere with 2-f operator



FCNC top decay

- FCNC top decays are measured at both Tevatron and LHC.
  - Br($t \to qZ$)<0.05%
  - Br($t \to q\gamma$)<3.2%
  - Br($t \to ch$)<0.56%

- FCNC production processes are also measured, e.g.
  - $e^+e^- \to tq$ at LEP2
  - $ep \to tq$ at HERA
  - $pp \to tj, t\gamma, tZ$ at Tevatron and LHC

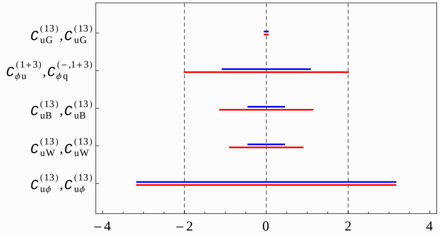
  and results may be converted to limits on branching ratios.

- However, the four-fermion contributions are not properly measured.

FCNC top decay

A simple "global fit": neglecting four-fermion operators, naively combine all decay measurements, $pp \to t(j)$ from ATLAS and $pp \to t\gamma$ from CMS
$\Rightarrow$ possible to constrain all FCNC two-fermion operators.

Limits on each operator



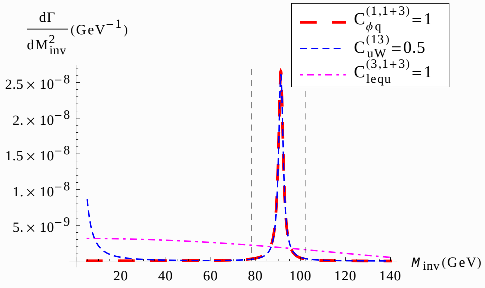
$\Lambda = 1$ TeV
Blue: setting all other operators to 0.
Red: floating all other operators.

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

$$O_{uW}^{(13)} = g_W(\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W_{\mu\nu}^I,\quad O_{uW}^{(31)} = g_W(\bar{Q}\sigma^{\mu\nu}\tau^I u)\tilde{\varphi}W_{\mu\nu}^I$$
$$O_{uB}^{(13)} = g_Y(\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu},\quad O_{uB}^{(31)} = g_Y(\bar{Q}\sigma^{\mu\nu} u)\tilde{\varphi}B_{\mu\nu}$$
$$O_{u\varphi}^{(13)} = (\varphi^\dagger\varphi)(\bar{q}t)\tilde{\varphi},\quad O_{u\varphi}^{(31)} = (\varphi^\dagger\varphi)(\bar{Q}u)\tilde{\varphi}$$
$$O_{uG}^{(13)} = g_s(\bar{q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G_{\mu\nu}^A,\quad O_{uG}^{(31)} = g_s(\bar{Q}\sigma^{\mu\nu}T^A u)\tilde{\varphi}G_{\mu\nu}^A$$

FCNC top decay, 4-fermion operator

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



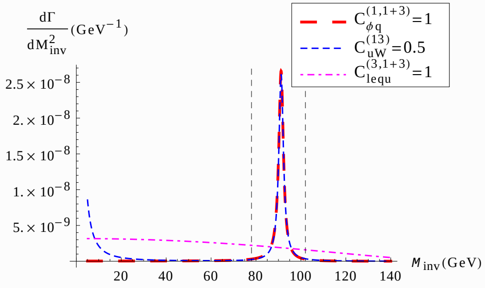
- 2-f operators ($O_{\varphi q}, O_{uW}\dots$), $t \to uZ$, $Z \to ll$. $\Rightarrow$ peak at Z mass.
- 4-f operators ($O_{lequ}^{(3,13)} = (\bar{l}\sigma_{\mu\nu}e)\,\varepsilon\,(\bar{q}\sigma^{\mu\nu}t)$), $t \to ull$. $\Rightarrow$ continuous spectrum.

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

$$\Gamma_{\rm on} = \left(7.0|C_{uW}^{(13)}|^2 + 1.8|C_{\varphi q}^{(1,1+3)}|^2 + 0.8|C_{lequ}^{(3,13)}|^2\right) \times 10^{-5}\ \mathrm{GeV}$$

FCNC top decay, 4-fermion operator

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 ($O^{(3,13)}_{lequ} = (\bar{l}\sigma_{\mu\nu}e)\,\varepsilon\,(\bar{q}\sigma^{\mu\nu}t)$), $t \to ull$.
  $\Rightarrow$ continuous spectrum.

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

$$\Gamma_{\mathrm{off}} = \left(0.6|C^{(13)}_{uW}|^2 + 0.1|C^{(1,1+3)}_{\varphi q}|^2 + 2.7|C^{(3,13)}_{lequ}|^2\right) \times 10^{-5}\ \mathrm{GeV}$$

4-fermion operator has a larger contribution. Might get improved limit on 4-fermion operator. Can disentangle 2-f and 4-f operators if signal is observed.

Outline

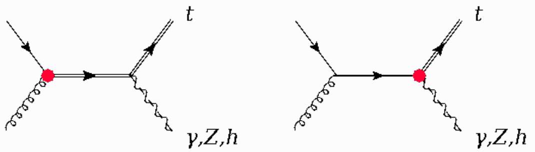
$pp \to tX$

Single top production can bring new information on top FCNC.
In particular, here we are interested in $pp \to t\gamma$, $pp \to tZ$, $pp \to th$.

- 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.
- Typical k factor ~ 1.3

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

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



$pp \to tX$

For real analysis it's desirable to have MC generators...

- Implementation of dim-6 FCNC (2-fermion) operators in aMC@NLO [1405.0301] is ongoing.
- 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/
```

$pp \to tX$

- Comparison with previous works:
  - $pp \to t\gamma$:

Y. Zhang et al.
1101.5346

$\kappa_{tq}^{\gamma} = 0.3$, 14 TeV (pb)

	1101.5346	aMC@NLO
κ_{tu}^{γ}, LO	3.78	3.777±0.0066
κ_{tu}^{γ}, NLO	5.16	5.117±0.027
κ_{tc}^{γ}, LO	0.386	0.3874±0.0007
κ_{tc}^{γ}, NLO	0.537	0.5208±0.0029

$\kappa_{tq}^{\gamma} = 0.02$, $\kappa_{tq}^{g} = 0.01$, 14 TeV (fb)

	1101.5346	aMC@NLO
κ_{tu}^{V}, LO	27.8	28.02±0.11
κ_{tu}^{V}, NLO	42.7	42.1±0.29
κ_{tc}^{V}, LO	3.13	3.139±0.012
κ_{tc}^{V}, NLO	5.61	5.373±0.013

  - $pp \to tZ$:

B. Li et al.
1103.5122

$\kappa_{tq}^{Z} = 0.5$, 14 TeV (pb)

	1103.5122	aMC@NLO
κ_{tu}^{Z}, LO	15.9	15.79±0.061
κ_{tu}^{Z}, NLO	22.5	22.18±0.082
κ_{tc}^{Z}, LO	1.29	1.27±0.0049
κ_{tc}^{Z}, NLO	1.85	1.753±0.011

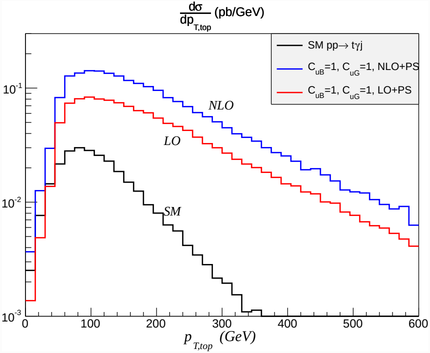
$\kappa_{tq}^{Z} = 0.5$, 1.96 TeV (fb)

	1103.5122	aMC@NLO
κ_{tu}^{Z}, LO	55.5	54.76±0.1
κ_{tu}^{Z}, NLO	88.6	87.45±0.44
κ_{tc}^{Z}, LO	1.62	1.607±0.0027
κ_{tc}^{Z}, NLO	2.45	2.461±0.0097

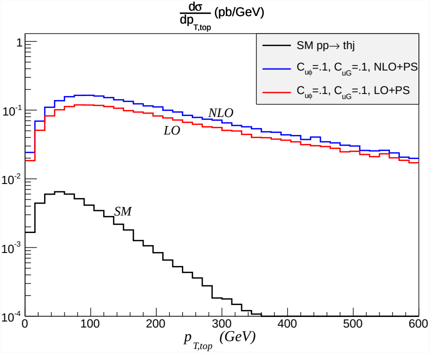
$pp \to tX$

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

Left: $pp \to t\gamma$ Right: $pp \to th$



$pp \to t\gamma$ 13 TeV



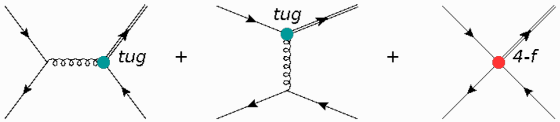
$pp \to th$ 13 TeV

More FCNC. . .

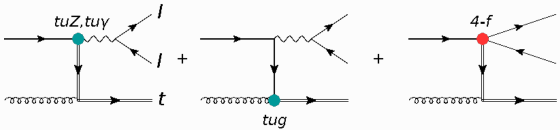
A rich set of processes will be studied at NLO(+PS)

- Single top, $pp \to t\gamma, tZ, th, tj, e^+e^- \to tj$, with 2-fermion operators.
- $pp \to t\bar{t}$ with FCNC top decay, or $h \to t^* u$ etc. . .
- More possibilities with four-fermion operators. . .

$pp \to tj$



$pp \to tll$ ($pp \to tZ$)



Outline

Summary

- EFT is a consistent and complete theoretical approach to NP, where predictions can be systematically improved.
- In top-quark physics, EFT is playing a more and more important role (making the field more and more like flavor physics. . .)
- NLO results in EFT framework:
  - One-loop anomalous dimensions for all dim-6 operators are known.
  - Analytical results for top-quark decay in EFT is available at NLO in QCD.
  - Implementation of top quark FCNC processes in MC generator at NLO is in progress.
  - The full EFT framework at NLO will be available in future.

Thank you!

Backups

2-fermion operators in top FCNC

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

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

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

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

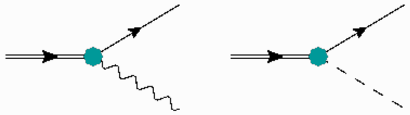
3. $(\bar{u}\sigma^{\mu\nu}q_{\nu}t)G_{\mu}$, “color dipole”

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

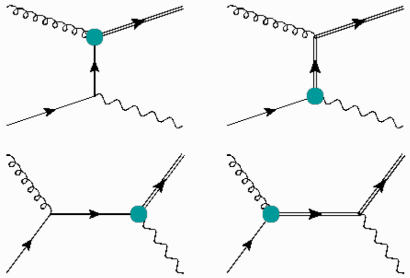
4. $\bar{u}th$, ”Yukawa”

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

FCNC t decay



FCNC t production



Top FCNC, 4-fermion operators

FCNC may be mediated by heavy particles.

- V-V

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

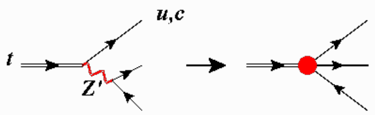
- S-S

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

- 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'



FCNC mixing

$$O_{uG}^{(13)} = y_t g_s (\bar{q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G_{\mu\nu}^A$$
$$O_{uW}^{(13)} = y_t g_W (\bar{q}\sigma^{\mu\nu} \tau^I t)\tilde{\varphi} W_{\mu\nu}^I$$
$$O_{uB}^{(13)} = y_t g_Y (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$
$$O_{u\varphi}^{(13)} = -y_t^3 (\varphi^\dagger \varphi)(\bar{q}t)\tilde{\varphi}$$

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

same for:

$$O_{uG}^{(31)} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A u)\tilde{\varphi} G_{\mu\nu}^A$$
$$O_{uW}^{(31)} = y_t g_W (\bar{Q}\sigma^{\mu\nu} \tau^I u)\tilde{\varphi} W_{\mu\nu}^I$$
$$O_{uB}^{(31)} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} u)\tilde{\varphi} B_{\mu\nu}$$
$$O_{u\varphi}^{(31)} = -y_t^3 (\varphi^\dagger \varphi)(\bar{Q}u)\tilde{\varphi}$$

$$O_{dG}^{(13)} = y_t g_s (\bar{q}\sigma^{\mu\nu} T^A b)\varphi G_{\mu\nu}^A$$
$$O_{dW}^{(13)} = y_t g_W (\bar{q}\sigma^{\mu\nu} \tau^I b)\varphi W_{\mu\nu}^I$$
$$O_{dB}^{(13)} = y_t g_Y (\bar{q}\sigma^{\mu\nu} b)\varphi B_{\mu\nu}$$
$$O_{d\varphi}^{(13)} = -y_t^3 (\varphi^\dagger \varphi)(\bar{q}b)\varphi$$

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

same for:

$$O_{dG}^{(31)} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A d)\varphi G_{\mu\nu}^A$$
$$O_{dW}^{(31)} = y_t g_W (\bar{Q}\sigma^{\mu\nu} \tau^I d)\varphi W_{\mu\nu}^I$$
$$O_{dB}^{(31)} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} d)\varphi B_{\mu\nu}$$
$$O_{d\varphi}^{(31)} = -y_t^3 (\varphi^\dagger \varphi)(\bar{Q}d)\varphi$$

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

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

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

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

Current Limits

- $qg \to t$:
  Br($t \to ug$)<3.1×10^{-5}, Br($t \to cg$)<1.6×10^{-4} **ATLAS-CONF-2013-063**
- $qg \to tZ$:
  Br($t \to ug$)<0.56%, Br($t \to cg$)<7.12%
  Br($t \to uZ$)<0.51%, Br($t \to cZ$)<11.4% **CMS PAS TOP-12-021**
- $qg \to t\gamma$:
  Br($t \to u\gamma$)<0.0161%, Br($t \to c\gamma$)<0.182% **CMS-PAS-TOP-14-003**
- $t \to qZ$:
  Br($t \to qZ$)<0.05% **CMS-TOP-12-037**
- $t \to qh$:
  Br($t \to ch$)<0.56% **CMS-PAS-HIG-13-034**

Projections

J.A. Aguilar-Saavedra
hep-ph/0409342

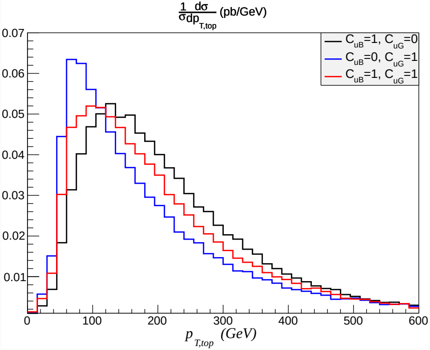
	Top decay	Single top		Top decay	Single top
$t \to uZ(\gamma_\mu)$	3.6×10^{-5}	8.0×10^{-5}	$t \to cZ(\gamma_\mu)$	3.6×10^{-5}	3.9×10^{-4}
$t \to uZ(\sigma_{\mu\nu})$	3.6×10^{-5}	2.3×10^{-5}	$t \to cZ(\sigma_{\mu\nu})$	3.6×10^{-5}	1.4×10^{-4}
$t \to u\gamma$	1.2×10^{-5}	3.1×10^{-6}	$t \to c\gamma$	1.2×10^{-5}	2.8×10^{-5}
$t \to ug$	–	2.5×10^{-6}	$t \to cg$	–	1.6×10^{-5}
$t \to uH$	5.8×10^{-5}	5.1×10^{-4}	$t \to cH$	5.8×10^{-5}	2.6×10^{-3}

Table 4: $3\,\sigma$ discovery limits for top FCN interactions at LHC, for an integrated luminosity of 100 fb^{-1}. The limits are expressed in terms of top decay branching ratios.

$pp \to tX$

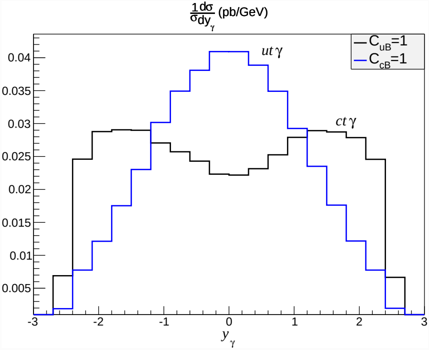
- Results for $pp \to t\gamma$, normalized distributions (Λ=1 TeV)

Left: O_{uB} and O_{uG} lead to different p_T distribution.
($ut\gamma$ vs. utg)



$pp \to t\gamma$ 13 TeV

Right: O_{uB} and O_{cB} lead to different y_γ distribution.
($ut\gamma$ vs. $ct\gamma$)



$pp \to t\gamma$ 13 TeV

Some numerical results for F_+ and F_0

$$F_0 = 0.689 - 0.039 C_{tW} + 0.0007 C_{tG}$$

$$F_+ = [1.69 - 0.10 C_{tW} + 0.03 C_{tG}] \times 10^{-3}$$

$$O_{tW} = y_t g_W \left(\bar{Q} \sigma^{\mu\nu} \tau^I t \right) \tilde{\varphi} W^I_{\mu\nu}$$

$$O_{tG} = y_t g_s \left(\bar{Q} \sigma^{\mu\nu} T^A t \right) \tilde{\varphi} G^A_{\mu\nu}$$