SMEFT at NLO in QCD

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Based on works in collaboration with O. B. Bylund, C. Degrande, G. Durieux, D. B. Franzosi, F. Maltoni, I. Tsinikos, E. Vryonidou, J. Wang.

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Outline

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Towards precision SMEFT

- Top/Higgs measurements are becoming precision measurements. Run-II analyses are underway. Theoretical predictions at the same level are mandatory.

- NNLO QCD + NLO EW is becoming standard in SM. For NP, i.e. dim-6, it's likely that NLO QCD is relevant.

  - In fact even NLO EW at dim-6 can be relevant: *[G. Degrassi et al.]*, *[M. Gorbahn, U. Haisch]*

Large correction $\Rightarrow$ better sensitivity

- Large QCD corrections to inclusive cross sections (i.e. large K factors) often increase the sensitivity to SM deviations at the $\mathcal{O}(1)$ level.
  - It is well known that the *ggH* operator — used in $gg \to H$ in the SM — has a K factor of ~ 2 at NLO.
  - Chromo-dipole operator in $t\bar{t}$ production, $K \approx 1.5$ at the LHC. Limits can be improved by more than 50% due to improved precision. *[D. Franzosi and CZ]*
  - Even larger effects in top-FCNC searches. *[Degrande, Maltoni, Wang, CZ]*
  - This is often not related to the large log terms $\log[\Lambda/m_H]$.

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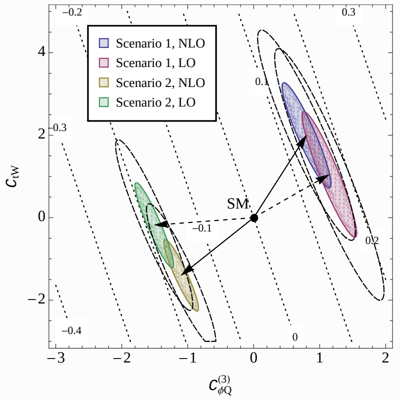
Shapes ⇒ avoid misidentification of NP

- EFT analyses have started to become sensitive to differential distribution of key observables, e.g.
  Higgs: [T. Corbett et al.] [A. Butter et al.] . . .
  Top: [A. Buckley et al.] [A. Buckley et al.]

- QCD corrections to shapes can lead to bias in fitting results.

- E.g. in single top, in case of 15% deviations observed in future, LO/NLO lead to a different direction of deviation from SM. (due to one operator at NLO becomes more like the other)

EFT fit to single top shapes [CZ]



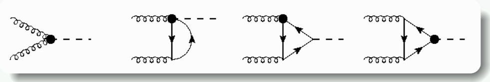
Better understanding of the theory

- "Loop-induced" scenarios: new operators enter at NLO, e.g. [C. Degrande et al.]

LO: $O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$

NLO: $O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q}t)\, \tilde{\phi}$

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



- RG effects: $dC_i/d\ln\mu = \gamma_{ij} C_j$, $\gamma_{ij} = 2499 \times 2499$ matrix.

  [E. Jenkins et al.] [E. Jenkins et al.] [R. Alonso et al.]

  - How well do they represent higher-order corrections?

- TH uncertainties.
  - In particular, scale dependence of C_i on the EFT scale induces new TH error. [Maltoni, Vryonidou, CZ]
  - Is μ_{EFT} scale uncertainty a good estimate for TH error?

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Some higher-order results in SMEFT

- Analytical (for the decay)
  - NLO top decay [CZ 14], [CZ, F. Maltoni 13] (see also [Drobnak, Fajfer, Kamenik 10], [Drobnak, Fajfer, Kamenik 10], [Drobnak, Fajfer, Kamenik 10], [J. J. Zhang et al. 10])
  - One-loop $h \to \gamma\gamma$ [C. Hartmann, M. Trott 15]
  - One-loop (4-fermion) $h \to b\bar{b}, \tau^+\tau^-$ [Gauld, Pecjak, Scott 15]; QCD NLO $h \to b\bar{b}$ [Gauld, Pecjak, Scott 16]
- Event generation (for the production)
  - VH, VBF (SILH) [C. Degrande et al. 16] (see also Higgs Characterisation e.g. [F. Demartin et al. 15])

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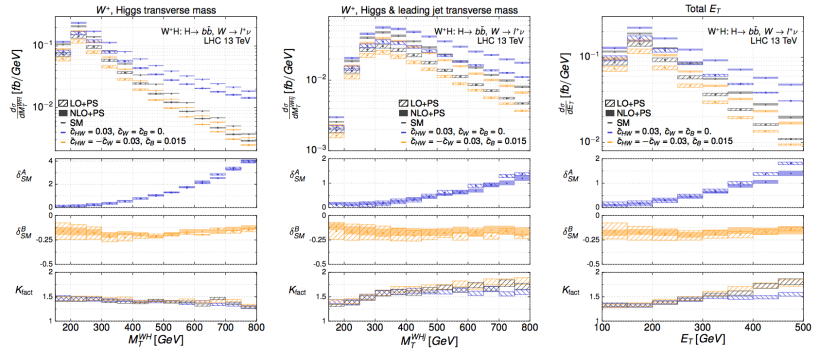
VH and VBF



- 5 Higgs operators in the SILH basis are included. Modifications of couplings and shifts in input parameters are considered.
- K factor independent of operators, but reduction of TH uncertainties helps to disentangle BSM effects.
- EFT validity: Run-II has the ability to set limits within the range of validity.

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  - $t\bar{t}Z$ production [R. Rontsch and M. Schulze 14], [R. Rontsch and M. Schulze 15]

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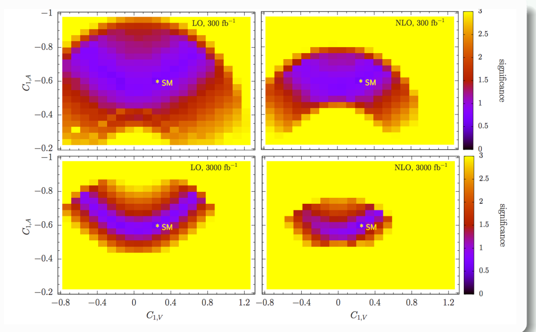
$t\bar{t}Z$

- $pp \to t\bar{t}Z/\gamma^* \to bjj\bar{b}l^-\bar{\nu}l^-l^+$, using the following Lagrangian

$$\mathcal{L}_{t\bar{t}Z} = e\bar{u}(p_t)\left[\gamma^\mu\left(C^Z_{1,V} + \gamma_5 C^\gamma_{q,A}\right) + \frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(C^Z_{2,V} + i\gamma_5 C^Z_{2,A}\right)\right]v(p_{\bar{t}})Z_\mu$$

- Cross section/distributions are computed. LHC (and ILC) potential is studied.



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  - 4-fermion operators in dijet and $t\bar{t}$ [J. Gao et al. 11] [D. Y. Shao et al. 11]
  - All top-quark production channels (including $t\bar{t}H$)

Our goal:

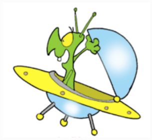
Extending SMEFT framework to NLO precision in the top-quark sector, by automating it the MadGraph5_aMC@NLO framework.

Outline

NLO implementation

Implement the effective operators as an "UFO" model.

[C. Degrande et al.]



- Despite that NLO UFO generation has been automated to some extend, SMEFT is a different theory—at dim-6—and serveral things need to be considered for an NLO automation.
- UV counterterms
  - Coming from the renormalization of SMEFT.
  - Running&mixing of coefficients: charatersized by 2499X2499 matrix.
    - First computed by [R. Alonso et al.] (and refs therein) but we always check.
  - Wave functions and masses, g_s etc. e.g. from O_{tG}

NLO implementation

- R2 counterterms
  - Loop amplitude: $\frac{1}{(2\pi)^4}\int d^d\bar{q}\frac{\bar{N}(\bar{q})}{\bar{D}_0\bar{D}_1\cdots\bar{D}_{m-1}}$, $\bar{D}_i=(\bar{q}+p_i)^2-m_i^2$
  - Problem: numerical technique only evaluates the 4-dimensional part.
  - Solution: isolate the ε-dim part of numerator: $\bar{N}(\bar{q})=N(q)+\tilde{N}(\tilde{q},q,\varepsilon)$ Then calculate ε part analytically, once and for all.

$$R2\equiv\lim_{\varepsilon\to 0}\frac{1}{(2\pi)^4}\int d^d\bar{q}\frac{\tilde{N}(\bar{q})}{\bar{D}_0\bar{D}_1\cdots\bar{D}_{m-1}}$$

- Need to be computed at dim-6 (NLOCT could help) [C. Degrande]
- There are also other sources, e.g. 4-fermion operators
  - Fermion flow at one loop: $\gamma^\mu P_L\otimes\gamma_\mu P_L\Rightarrow\gamma^\mu\gamma^\nu\gamma^\rho P_L\otimes\gamma_\mu\gamma_\nu\gamma_\rho P_L$
  - Problem: Cannot be reduced to the standard 4-fermion operator basis (which is not complete in D dimension)
  - Solution: Need to define E="evanescent" operators, $\gamma^\mu\gamma^\nu\gamma^\rho P_L\otimes\gamma_\mu\gamma_\nu\gamma_\rho P_L=4(4-(x)\varepsilon)\gamma^\mu P_L\otimes\gamma_\mu P_L+E$
  - Result: Scheme dependence enters R2.

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  - Result: Scheme dependence enters R2.

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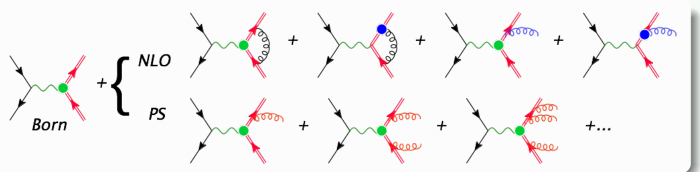
For the users

- Get MG5_aMC, and the EFT UFO.
- Type

```
MG_DIR>./bin/mg5
MG5_aMC>import model TEFT
MG5_aMC>generate e- e+ > t t~ EFT=1 [QCD]
MG5_aMC>output some_DIR
MG5_aMC>launch
```

- MG will generate codes for:



- i.e. with virtual & real corrections, parton shower (MC@NLO), and decays with spin correlation (MADSPIN). [S. Frixione and B. Webber] [P. Artoisenet et al.]

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$pp \to t\bar{t}H$

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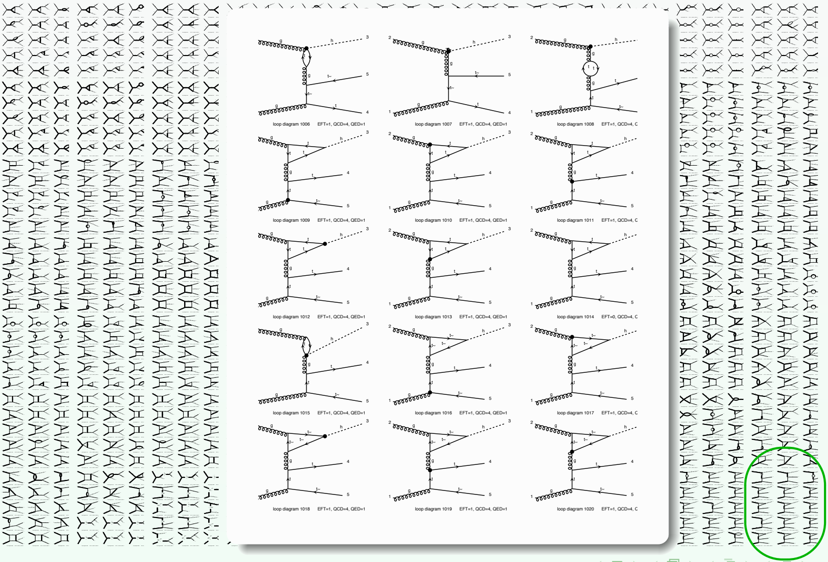
loop diagram 1006 EFT=1, QCD=4, QED=1
loop diagram 1007 EFT=1, QCD=4, QED=1
loop diagram 1008 EFT=1, QCD=4, C
loop diagram 1009 EFT=1, QCD=4, QED=1
loop diagram 1010 EFT=1, QCD=4, QED=1
loop diagram 1011 EFT=1, QCD=4, C
loop diagram 1012 EFT=1, QCD=4, QED=1
loop diagram 1013 EFT=1, QCD=4, QED=1
loop diagram 1014 EFT=0, QCD=4, C
loop diagram 1015 EFT=1, QCD=4, QED=1
loop diagram 1016 EFT=1, QCD=4, QED=1
loop diagram 1017 EFT=1, QCD=4, C
loop diagram 1018 EFT=1, QCD=4, QED=1
loop diagram 1019 EFT=1, QCD=4, QED=1
loop diagram 1020 EFT=1, QCD=4, C

Outline

1. Top-EW operators

- Electroweak operators:
  - For testing $tbW/ttZ/tt\gamma$ couplings.
  - Key processes: single top, $pp \to t\bar{t} + V$, $pp \to tj + V$, and $e^+e^- \to t\bar{t}$.

[CZ] [Bylund, Maltoni, Tsinikos, Vryonidou, CZ]

for ttZ see also: [R. Rontsch and M. Schulze] [R. Rontsch and M. Schulze]

Full set of top-EW couplings

- $tt\gamma/ttg$, 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/dipole
  - 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/dipole
  - 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}

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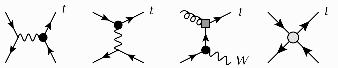
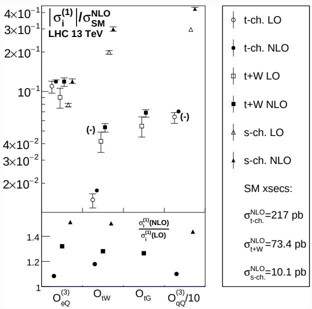
Single top at NLO

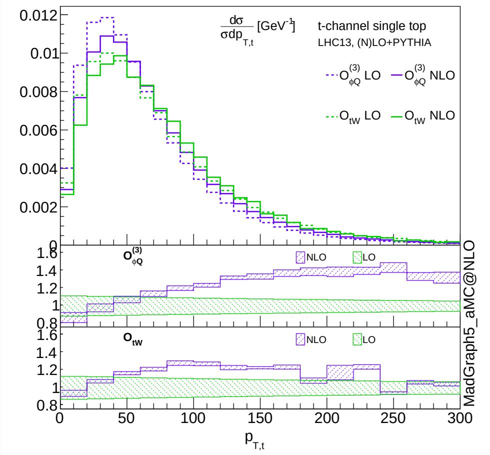
Single t: s-, t-, and tW channels



Single top xsecs

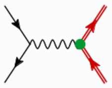


p_T distribution in t-channel (normalized)

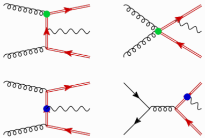


$pp \to t\bar{t}V$ and $e^+e^- \to t\bar{t}$ at NLO

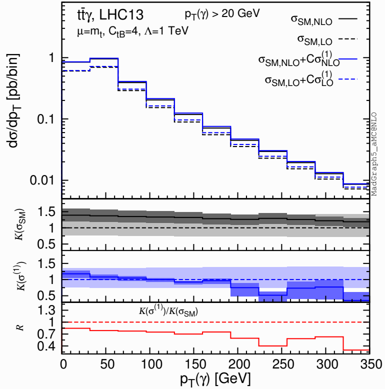
$e^+e^- \to t\bar{t}$



$tt\gamma / ttZ$



$tt\gamma$, $p_T(\gamma)$ distribution and K factor



$t\bar{t}$ cross sections at ILC

500GeV	SM	$\mathcal{O}_{tG}$	$\mathcal{O}_{\phi Q}^{(3)}$	$\mathcal{O}_{\phi Q}^{(1)}$	$\mathcal{O}_{\phi t}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{tB}$
$\sigma_{i,LO}^{(1)}$	566	0	15.3	-15.3	-1.3	272	191
$\sigma_{i,NLO}^{(1)}$	647	-6.22	18.0	-18.0	-1.0	307	216
K-factor	1.14	N/A	1.17	1.17	0.78	1.13	1.13
$\sigma_{i,LO}^{(2)}$		0	0.72	0.71	0.72	60.4	27.2
$\sigma_{i,NLO}^{(2)}$		0.037	0.83	0.82	0.82	68.8	31.0

2. Top+Higgs: O_{tG}, $O_{\phi G}$, $O_{t\phi}$

- In this case we are interested in operators involving $t/H/g$ fields.

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q}t)\, \tilde{\phi}$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

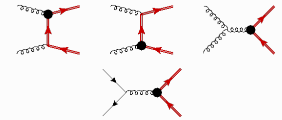
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}$$

- In particular, Higgs cross section constrains only a combination of O_{tG}, $O_{\phi G}$, and $O_{t\phi}$. Need other processes to resolve.

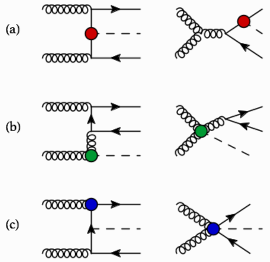
  [C. Grojean et al.] [Q.-H. Cao et al.] [A. Azatov et al.]. . .

- Key processes:
  - (NLO) $t\bar{t}$ production, constraining O_{tG}
  - (NLO) $pp \to t\bar{t}H$, all 3 operators
  - (LO) Loop-induced processes:
    - $gg \to H$, all 3 operators
    - $gg \to Hj, HH, \cdots$

$pp \to t\bar{t}$: O_{tG}



$pp \to t\bar{t}H$: O_{tG}, $O_{\phi G}$, $O_{t\phi}$



$pp \to t\bar{t}$: O_{tG}

Top chromo-dipole moment O_{tG} in $t\bar{t}$ production:

- Cross sections

O_{tG} cross sections ($C_{tG}/\Lambda^2 = 1/\text{TeV}^2$)

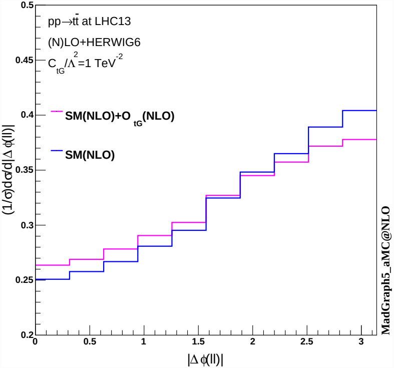
β_1	LO [pb TeV^2]	NLO [pb TeV^2]	K factor
Tevatron	$1.61^{+0.66}_{-0.43}$ $^{(+41\%)}_{(-27\%)}$	$1.810^{+0.073}_{-0.197}$ $^{(+4.05\%)}_{(-10.88\%)}$	1.12
LHC8	$50.7^{+17.3}_{-12.4}$ $^{(+34\%)}_{(-25\%)}$	$72.62^{+9.26}_{-10.53}$ $^{(+12.7\%)}_{(-14.5\%)}$	1.43
LHC13	$161.6^{+48.0}_{-36.2}$ $^{(+29.7\%)}_{(-22.4\%)}$	$239.5^{+29.0}_{-31.8}$ $^{(+12.1\%)}_{(-13.3\%)}$	1.48
LHC14	$191.3^{+55.6}_{-42.2}$ $^{(+29.0\%)}_{(-22.0\%)}$	$283.0^{+33.6}_{-36.9}$ $^{(+11.9\%)}_{(-13.1\%)}$	1.48

Limits on C_{tG}/Λ^2

	LO [TeV^{-2}]	NLO [TeV^{-2}]
Tevatron	[-0.33, 0.75]	[-0.32, 0.73]
LHC8	[-0.56, 0.41]	[-0.42, 0.30]
LHC14	[-0.56, 0.61]	[-0.39, 0.43]

- Distributions
  E.g. $A_{FB} = 0.095 + C_{tG} \times 0.021(\text{TeV}/\Lambda)^2$
- Spin correlation taken into account by MADSPIN.

Decayed top: spin correlation



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$t\bar{t}H$ production

$$\sigma = \sigma_{SM} + \sum_i \frac{1\mathrm{TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i\leq j} \frac{1\mathrm{TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}$$

13 TeV	σ LO	σ/σ_{SM} LO	σ NLO	σ/σ_{SM} NLO	K
σ_{SM}	$0.464^{+0.161+0.000+0.005}_{-0.111-0.000-0.004}$	$1.000^{+0.000+0.000+0.000}_{-0.000-0.000-0.000}$	$0.507^{+0.030+0.000+0.007}_{-0.048-0.000-0.008}$	$1.000^{+0.000+0.000+0.000}_{-0.000-0.000-0.000}$	1.09
$\sigma_{t\phi}$	$-0.055^{+0.013+0.002+0.000}_{-0.019-0.003-0.001}$	$-0.119^{+0.000+0.005+0.000}_{-0.000-0.006-0.000}$	$-0.062^{+0.006+0.001+0.001}_{-0.004-0.001-0.001}$	$-0.123^{+0.001+0.001+0.000}_{-0.001-0.002-0.000}$	1.13
$\sigma_{\phi G}$	$0.627^{+0.225+0.081+0.007}_{-0.153-0.067-0.005}$	$1.351^{+0.011+0.175+0.002}_{-0.011-0.145-0.001}$	$0.872^{+0.131+0.037+0.013}_{-0.123-0.035-0.016}$	$1.722^{+0.146+0.073+0.004}_{-0.089-0.068-0.005}$	1.39
σ_{tG}	$0.470^{+0.167+0.000+0.005}_{-0.114-0.002-0.004}$	$1.014^{+0.006+0.000+0.001}_{-0.006-0.004-0.001}$	$0.503^{+0.025+0.001+0.007}_{-0.046-0.003-0.008}$	$0.991^{+0.004+0.003+0.000}_{-0.010-0.006-0.001}$	1.07
$\sigma_{t\phi,t\phi}$	$0.0016^{+0.0005+0.0002+0.0000}_{-0.0004-0.0001-0.0000}$	$0.0035^{+0.0000+0.0004+0.0000}_{-0.0000-0.0003-0.0000}$	$0.0019^{+0.0001+0.0001+0.0000}_{-0.0002-0.0000-0.0000}$	$0.0037^{+0.0001+0.0002+0.0000}_{-0.0000-0.0001-0.0000}$	1.17
$\sigma_{\phi G,\phi G}$	$0.646^{+0.274+0.141+0.018}_{-0.178-0.107-0.010}$	$1.392^{+0.079+0.304+0.025}_{-0.066-0.231-0.014}$	$1.021^{+0.204+0.096+0.024}_{-0.178-0.085-0.029}$	$2.016^{+0.267+0.190+0.021}_{-0.178-0.167-0.027}$	1.58
$\sigma_{tG,tG}$	$0.645^{+0.276+0.011+0.020}_{-0.178-0.015-0.010}$	$1.390^{+0.082+0.023+0.028}_{-0.069-0.031-0.016}$	$0.674^{+0.036+0.004+0.016}_{-0.067-0.007-0.019}$	$1.328^{+0.011+0.008+0.014}_{-0.038-0.014-0.018}$	1.04
$\sigma_{t\phi,\phi G}$	$-0.037^{+0.009+0.006+0.000}_{-0.013-0.007-0.000}$	$-0.081^{+0.001+0.012+0.000}_{-0.001-0.015-0.000}$	$-0.053^{+0.008+0.003+0.001}_{-0.008-0.004-0.001}$	$-0.105^{+0.006+0.006+0.000}_{-0.009-0.007-0.000}$	1.42
$\sigma_{t\phi,tG}$	$-0.028^{+0.007+0.001+0.000}_{-0.010-0.001-0.000}$	$-0.060^{+0.000+0.002+0.000}_{-0.000-0.003-0.000}$	$-0.031^{+0.003+0.000+0.000}_{-0.002-0.000-0.000}$	$-0.061^{+0.000+0.000+0.000}_{-0.000-0.001-0.000}$	1.10
$\sigma_{\phi G,tG}$	$0.627^{+0.252+0.053+0.014}_{-0.166-0.047-0.008}$	$1.349^{+0.054+0.114+0.016}_{-0.046-0.100-0.009}$	$0.859^{+0.127+0.021+0.017}_{-0.126-0.020-0.022}$	$1.691^{+0.137+0.042+0.013}_{-0.097-0.039-0.017}$	1.37

- We quote three TH errors: $\mu_{R,F}$ scale uncertainty, μ_{EFT} scale uncertainty, and PDF uncertainty.
- μ_{EFT} scale uncertainty is due to scale dependence of operator coefficients — including operator mixing effects.
  - $C_{tG} \to C_{\phi G} \to C_{t\phi}$

Mixing of $\{O_{t\phi}, O_{\phi G}, O_{tG}\}$

$$\frac{dC_i(\mu)}{d\log\mu} = \frac{\alpha_s}{\pi}\gamma_{ij}C_j(\mu)$$

$$\gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix}$$

New scale uncertainty from EFT running

- Apart from running of α_s, the running of C_i introduces additional scale uncertainties. Let μ_{EFT} be the scale where we define an EFT.

$$\sigma = \sigma_{SM} + \sum_i \frac{1\mathrm{TeV}^2}{\Lambda^2} C_i(\mu_{EFT})\sigma_i(\mu_{EFT}) + \sum_{i,j} \frac{1\mathrm{TeV}^4}{\Lambda^4} C_i(\mu_{EFT})C_j(\mu_{EFT})\sigma_{ij}(\mu_{EFT})$$

- The TH uncertainty due to μ_{EFT} (around a central scale μ_0) is estimated by

$$\sigma_i(\mu_0;\mu) = \Gamma_{ji}(\mu,\mu_0)\sigma_j(\mu) \ ,$$
$$\sigma_{ij}(\mu_0;\mu) = \Gamma_{ki}(\mu,\mu_0)\Gamma_{lj}(\mu,\mu_0)\sigma_{kl}(\mu) \ .$$

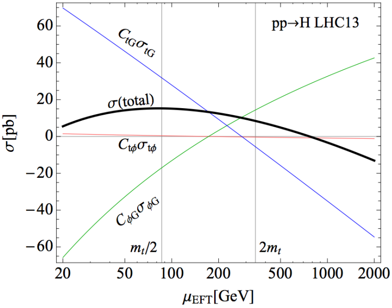
varying μ from $\mu_0/2$ to $2\mu_0$, and Γ_{ij} is the running matrix:

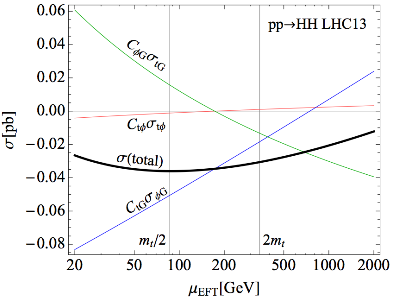
$$C_i(\mu) = \Gamma_{ij}(\mu,\mu_0)C_j(\mu_0)$$

New scale uncertainty from EFT running

E.g. consider O_{tG} contribution to loop-induced $pp \to H, HH$ (setting other operators to 0), the uncertainty is characterized by $\sigma_{tG}(m_t; \mu_{EFT})$.

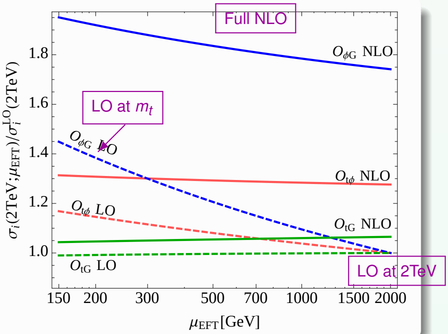
$pp \to H, HH$





$t\bar{t}H$: RG vs full NLO

- How much of the full NLO corrections are coming from renormalization group (RG) running?
- Are NLO dominated by $\log(\Lambda/m_H)$ terms?
- Or QCD corrections can be much more important than logs?



- Suppose a full theory is matched to an EFT with $O_{t\phi}$, $O_{\phi G}$, O_{tG} at 2 TeV.
- We can compute σ at LO $\mu = 2$ TeV, where we normalize results to 1.
- We can also improve these results by running the theory to m_t, and do another LO calculation. This increases σ by $0 \sim 50\%$ depending on operators.
- However the full NLO corrections are much larger.

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3. Top FCNC

- FCNC operators:
  - For testing $qtg/qtZ/qt\gamma/qtH$ couplings.
  - Key processes: $q+g\to t$, $q+g\to t+Z/\gamma/H$, and $e^+e^- \to tj$

[Degrande, Maltoni, Wang, CZ] [Durieux, Maltoni, CZ]

FCNC operators

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

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

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

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

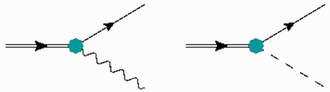
3. $(\bar{u}\sigma^{\mu\nu}q_{\nu}t)G_{\mu}$, “color dipole”

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

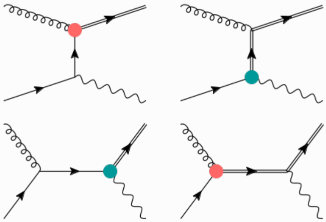
4. $\bar{u}th$, ”Yukawa”

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

FCNC t decay



FCNC t production



FCNC cross sections

Some cross sections have been validated with [J. Gao et al.] [Y. Zhang et al.] [B. H. Li et al.] [Y. Wang et al.]

$pp \to tZ$

	LO		NLO	
Coefficient	σ[fb]	Scale uncertainty	σ[fb]	Scale uncertainty
$C_{\varphi u}^{(1+3)} = 1.0$	905	$+12.9\% - 10.9\%$	1163	$+6.2\% - 5.6\%$
$C_{uW}^{(13)} = 0.9$	1737	$+11.5\% - 9.8\%$	2270	$+6.6\% - 6.2\%$
$C_{uG}^{(13)} = 0.04$	30.1	$+17.5\% - 13.8\%$	36.0	$+3.8\% - 5.2\%$
$C_{uG}^{(31)} = 0.04$	29.4	$+17.7\% - 13.9\%$	34.9	$+3.4\% - 5.1\%$
$C_{\varphi u}^{(2+3)} = 1.0$	73.2	$+10.4\% - 9.3\%$	107	$+6.5\% - 5.9\%$
$C_{uW}^{(23)} = 1.1$	172	$+7.5\% - 7.2\%$	255	$+6.1\% - 5.2\%$
$C_{uG}^{(23)} = 0.09$	6.92	$+11.3\% - 9.9\%$	10.6	$+5.8\% - 5.4\%$
$C_{uG}^{(32)} = 0.09$	6.58	$+11.5\% - 10.1\%$	10.0	$+5.7\% - 5.3\%$

$pp \to t\gamma$

	LO		NLO	
Coefficient	σ[fb]	Scale uncertainty	σ[fb]	Scale uncertainty
$C_{uB}^{(13)} = 1.0$	546	$+14.4\% - 11.8\%$	764	$+6.9\% - 6.4\%$
$C_{uG}^{(13)} = 0.04$	1.00	$+12.0\% - 10.2\%$	2.34	$+15.2\% - 11.5\%$
$C_{uG}^{(13)}$, veto	0.739	$+11.50\% - 9.8\%$	1.19	$+7.7\% - 6.5\%$
$C_{uB}^{(23)} = 1.9$	152	$+10.6\% - 9.6\%$	258	$+6.8\% - 6.0\%$
$C_{uG}^{(23)} = 0.09$	0.590	$+12.1\% - 11.1\%$	1.95	$+16.4\% - 12.3\%$
$C_{uG}^{(23)}$, veto	0.457	$+12.2\% - 11.2\%$	1.04	$+10.3\% - 8.9\%$

$pp \to tH$

	LO		NLO	
Coefficient	σ[fb]	Scale uncertainty	σ[fb]	Scale uncertainty
$C_{u\varphi}^{(13)} = 3.5$	2603	$+13.0\% - 11.0\%$	3858	$+7.4\% - 6.7\%$
$C_{uG}^{(13)} = 0.04$	40.1	$+16.5\% - 13.2\%$	50.7	$+4.0\% - 5.2\%$
$C_{u\varphi}^{(23)} = 3.5$	171	$+9.7\% - 8.7\%$	310	$+7.3\% - 6.3\%$
$C_{uG}^{(23)} = 0.09$	9.53	$+11.0\% - 9.7\%$	16.6	$+5.5\% - 5.1\%$

Summary

- NLO predicitons in SMEFT are needed for precision pheno, have impacts on global analyses, and improve our understanding of the theory.
- They have started to appear in the past several years, in both the Higgs/EW and the top-quark sectors.
- Systematic developments have started, based on the automatic MadGraph5_aMC@NLO framework. Main production channels of top and Higgs are becoming available. Results can be directly used in experimental analyses.

Backups

MEM

Operator	Uncertainty on $c_i\Lambda^{-2}$ (TeV^{-2})		
	Yields only	$\Delta\phi(l^+, l^-)$	Variable D_i
$\mathcal{O}_{tG}$	0.0057	0.0057	0.0057
$\mathcal{O}_{G}$	0.072	0.071	0.049
$\mathcal{O}_{\phi G}$	0.19	0.18	0.17
$\mathcal{O}_{qq}^{(8,1)}$	0.32	0.31	0.24
$\mathcal{O}_{qq}^{(8,3)}$	2.23	2.06	1.29
$\mathcal{O}_{ut}^{(8)}$	0.55	0.46	0.36
$\mathcal{O}_{dt}^{(8)}$	0.73	0.63	0.50

[Vincent Lemaitre, Sebastien Brochet, Sebastien Wertz]

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