Standard Model Effective Field Theory for Top Quark Physics

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Based on 1804.07773
(C. Degrande, F. Maltoni, K. Mimasu, E. Vryonidou, CZ),
and 1804.09766 (E .Vryonidou, CZ)

Outline

1. EFT interpretation of top measurements
2. Top EFT @ NLO QCD
   - Why we need NLO
   - Available processes and operators
   - Single top plus H/Z
   - Future plan
3. EW corrections
   - Higgs production & decay
4. Summary

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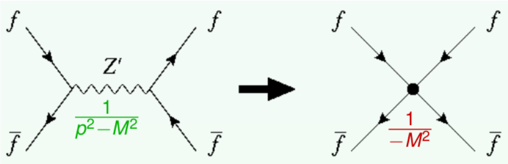
SMEFT

Starting with some BSM models

- Integrating out heavy states.
- Expanding the resulting non-standard interactions as a series of higher-dimensional operators.



$$\frac{1}{p^2-M^2} = \frac{1}{-M^2}\left[1 + \left(\frac{p^2}{M^2}\right) + \left(\frac{p^2}{M^2}\right)^2 + \cdots\right]$$

$$\mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4} O_i^{(8)} + \cdots$$

SMEFT at dim-6

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

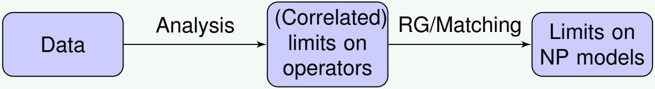
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu \tau^I q_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

[B. Grzadkowski et al,'10]

Why useful?

- Efficiency: analysis done once and for all



- Precision: predictions can be systematically improved.
  - Renormalizability, Gauge symmetries, estimate of TH uncertainties. . .
  - NLO QCD already available in many cases. EW corrections are being studied and even automated.
- Global approach: capture the interplay between different sectors/measurements.
  - Higgs, top, EW, TGC, flavor,. . .

[A. Falkowski et al., '15]

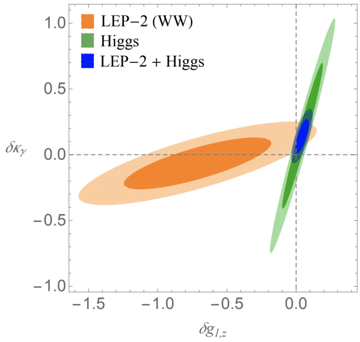


FIG. 1. Allowed 68% and 95% CL region in the $\delta g_{1,z}$-$\delta\kappa_\gamma$ plane after considering LEP-2 WW production data (TGC), Higgs data, and the combination of both datasets.

First step taken by the TopFitter Collaboration *[A. Buckley et al.'17]*

Top-quark operators and how to look for them

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)\left(\bar{Q}\gamma^\mu \tau^I Q\right)$$

$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{Q}\gamma^\mu Q\right)$$

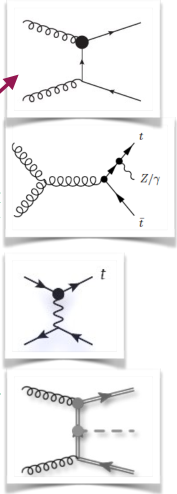
$$O_{\varphi t} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{t}\gamma^\mu t\right)$$

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

$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$

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

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



see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)

+four-fermion operators

+non-top operators (mixing)

Operators entering various processes: Global approach needed

In practice, we need a roadmap. . .

Interpreting top-quark LHC measurements in the standard-model effective field theory

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[J. Aguilar Saavedra et al.,'18]

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3 Operator definitions

4 Flavour assumptions

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A Indicative constraints

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C Flavour-, *B*- and *L*-conserving degrees of freedom

D Less restrictive flavour symmetry

E FCNC degrees of freedom

Interpreting top LHC measurements

- Reduce the number of OPs to start with (avoid 500+ 4-fermion OPs):

  Baseline $U(2)_q \times U(2)_u \times U(2)_d$:
  Forces the first two generation to appear as $\bar{q}q$, $\bar{u}u$, $\bar{d}d$.

  Extended $U(2)_{q+d+u}$:
  Allows right-handed $\bar{u}d$ and light chirality flipping ones $\bar{q}u$, $\bar{q}d$.

  Restricted Top-philic:
  All operators with SM bosons and (just) top. (and reduced to Warsaw basis)

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- Define the relevant degrees of freedom natural for top physics, and fix notations.

Top-specific d.o.f. definitions

Match SM interference structures
and interactions with physical gauge bosons

- $$\begin{pmatrix} O^{1(33)}_{\varphi q} \\ O^{3(33)}_{\varphi q} \end{pmatrix} = \begin{pmatrix} (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_3\gamma^\mu q_3) \\ (\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_3\gamma^\mu \tau^I q_3) \end{pmatrix} = \begin{pmatrix} -1 & 1 \\ 1 & 1 \\ 0 & 1 \\ 0 & 1 \end{pmatrix}^T \begin{pmatrix} \frac{+e}{2s_w c_w} & (\bar{t}\gamma^\mu P_L t) & Z_\mu & (v+h)^2 \\ \frac{-e}{2s_w c_w} & (\bar{b}\gamma^\mu P_L b) & Z_\mu & (v+h)^2 \\ \frac{g}{\sqrt{2}} & (\bar{t}\gamma^\mu P_L b) & W^+_\mu & (v+h)^2 \\ \frac{g}{\sqrt{2}} & (\bar{b}\gamma^\mu P_L t) & W^-_\mu & (v+h)^2 \end{pmatrix}$$

  $c^-_{\varphi Q} \equiv C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q}$ enters in $pp \to t\bar{t}Z$
  $c^3_{\varphi Q} \equiv C^{3(33)}_{\varphi q}$ enters in $t \to bW^+$
  $c^+_{\varphi Q} \equiv C^{1(33)}_{\varphi q} + C^{3(33)}_{\varphi q}$ enters in $e^+e^- \to b\bar{b}$ (or $pp \to b\bar{b}Z$)

- $$\begin{pmatrix} O^{1(ii33)}_{qq} \\ O^{1(i33i)}_{qq} \\ O^{3(ii33)}_{qq} \\ O^{3(i33i)}_{qq} \end{pmatrix} = \begin{pmatrix} 1 & 1/6 & 0 & 1/2 \\ 0 & 1/6 & 1 & -1/6 \\ 0 & 1 & 0 & 3 \\ 0 & 1 & 0 & -1 \end{pmatrix}^T \begin{pmatrix} (\bar{q}_i\gamma^\mu q_i)\,(\bar{Q}\gamma_\mu Q) \\ (\bar{q}_i\gamma^\mu \tau^I q_i)\,(\bar{Q}\gamma_\mu \tau^I Q) \\ (\bar{q}_i\gamma^\mu T^A q_i)\,(\bar{Q}\gamma_\mu T^A Q) \\ (\bar{q}_i\gamma^\mu \tau^I T^A q_i)\,(\bar{Q}\gamma_\mu \tau^I T^A Q) \end{pmatrix}$$

  $c^{1,1}_{Qq} \equiv C^{1(ii33)}_{qq} + \frac{1}{6}C^{1(i33i)}_{qq} + \frac{1}{2}C^{3(i33i)}_{qq}$ interferes with EW NC
  $c^{3,1}_{Qq} \equiv C^{3(ii33)}_{qq} + \frac{1}{6}(C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq})$ interferes with EW CC
  $c^{1,8}_{Qq} \equiv C^{1(i33i)}_{qq} + 3C^{3(i33i)}_{qq}$, interferes with QCD
  $c^{3,8}_{Qq} \equiv C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}$ doesn't interfere with EW CC

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- Provide simulation tools and benchmarks: DIM6TOP

  https://feynrules.irmp.ucl.ac.be/wiki/dim6top

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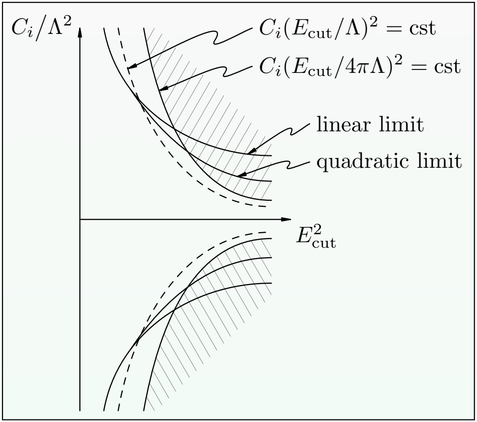
- Strategy.



- Quote limits as a function of E_{cut} [Contino,Falkowski,Goertz,Grojean,Riva,'16]
  - Assess the validity of matching to models.
  - Compare with perturbativity.

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Why we need NLO

- SMEFT is renormalizable order by order in $1/\Lambda$.
- We need higher-order corrections to control TH uncertainties for two classes of reasons:
  - Same as for SM: QCD corrections are important at hadron colliders; EW corrections are important for accuracy and for specific areas of phase space and observables; NLO corrections affect normalization, shapes, scale and PDF uncertainties.
  - Specific issues for SMEFT at dim>4: NLO could be the first order where non-trivial EFT structure becomes manifest: mixing, μ_{EFT} dependence, new contributions arise at NLO,...

Running & Mixing

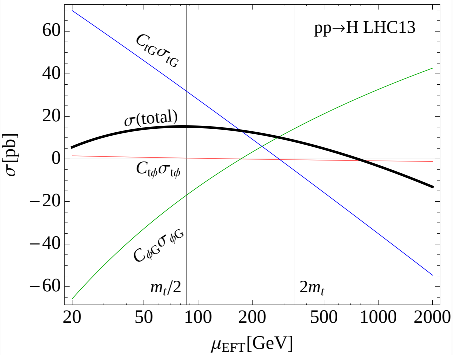
- Scale separation: coefficients are matched to BSM at scale Λ, but are probed at much lower scales.
- Coefficients are defined with MSbar scheme to take care of the logs.
- This means coefficients depend on the scale at which they are defined.
- RG mixing [R. Alonso et al., '13,'14]

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

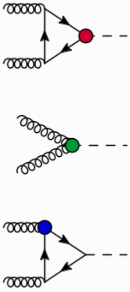
- One immediate consequence is that assumptions about some coefficients being zero at low scales are not valid.

EFT scale dependence

$gg \to H$ scale dependence



Op and diagrams



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

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

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

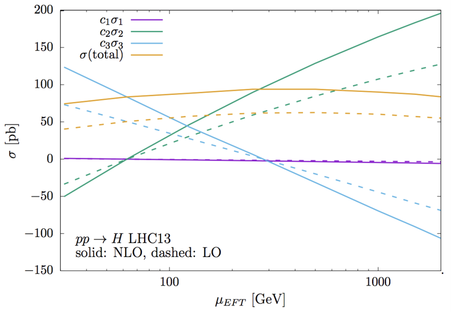
[Vryonidou, Maltoni, **CZ**, ’16]

$\Leftarrow C_{tG} = 1,\ C_{t\varphi} = C_{\varphi G} = 0$ at m_t.

- Scale dependence of (LO) $O_{\varphi G}$, from running coef., cancels that of (NLO) O_{tG}, from the loop.
- Only global point of view could make sense. To estimate TH uncertainty, must sum all ops.

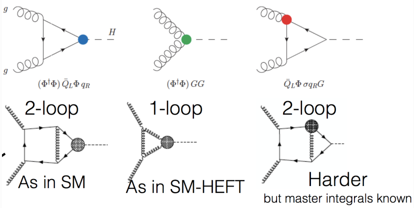
EFT scale dependence: even higher order

$gg \to H$ scale dependence



Op and diagrams

LO⇓



NLO⇑

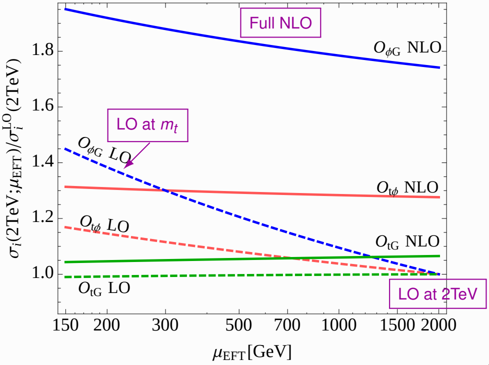
[Deutschmann, Duhr, Maltoni, Vryonidou, ’17]

- Once global, SMEFT prediction can be improved order by order.

Genuine NLO corrections can be large

- RG structure of SMEFT is process and observable-independent, but does not fully encode the NLO corrections.
  - In fact, they are NOT part of NLO correction from a bottom-up point of view.
- In contrast, the finite terms depend on processes and observables. Need to be studied on a process-by-process basis.
- Often, they are the **dominant** effects.

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



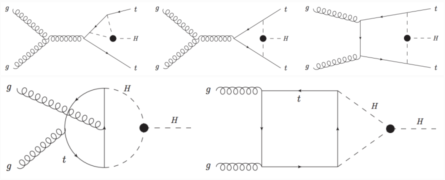
- Suppose a full theory is matched to an EFT with $O_{t\phi}$, $O_{\phi G}$, O_{tG} at 2 TeV.
- We can compute σ at LO $\mu = 2$ TeV, where we normalize results to 1.
- We can also improve these results by running the theory to m_t, and do another LO calculation. This increases σ by $0 \sim 50\%$ depending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

[Vryonidou, Maltoni, **CZ**, '16]

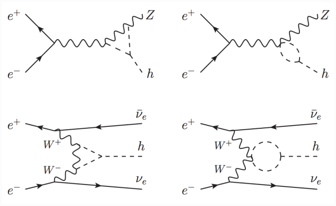
- Finite (QCD) corrections can be very important.
  - Similar cases in H and Z decay, see e.g. [R. Gauld, '16], [C. Hartmann, '16]
- Not to say RGEs are useless, but relying on them could be misleading.

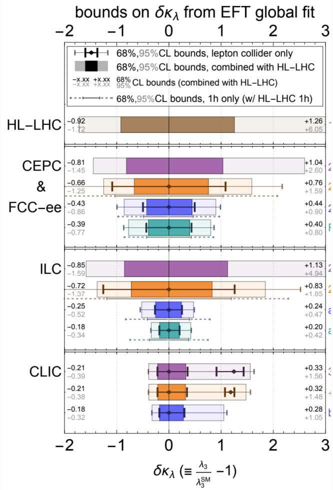
New operators arise at NLO

κ_λ at LHC [G. Degrassi et al., '16] [Gorbahn&Haisch, '16]



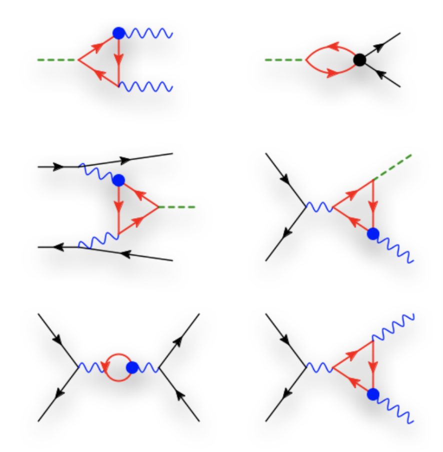
κ_λ at e^+e^- [M. McCullough, '13] [S. D. Vita et al., '17]





New operators arise at NLO

Top loops in Higgs processes



[E. Vryonidou and **CZ**, '18]

Potentially large effects:

$$\frac{\sigma_{loop}}{\sigma_{tree}} \sim \alpha_{EW} \frac{C_{top}}{C_{Higgs}}$$

given that top operator constraints are in general much weaker.

One last reason for going to NLO. . .

If it's "free".

```
MG5_aMC>import model TopEFT
MG5_aMC>generate p p > t t~ EFT=1 [QCD]
MG5_aMC>output
MG5_aMC>launch
```

(imagine this is all you need to get (NLO+PS) events. . .)

Outline

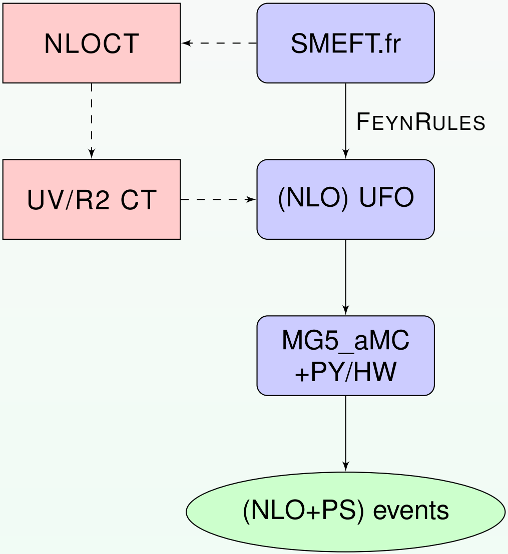
1 EFT interpretation of top measurements

2 Top EFT @ NLO QCD
- Why we need NLO
- Available processes and operators
- Single top plus H/Z
- Future plan

3 EW corrections
- Higgs production & decay

4 Summary

Workflow (ideally) NLO



[C. Degrande,'14]

Strategy

- Instead of having the full SMEFT@NLO automation, we start with important processes, one by one, to make sure nothing goes wrong.
- This also allows us to identify the potential complication due to going to higher-dim, which is crucial for the final automation of the full theory.

Status for top processes

	ttg	ttZ/γ, tbW					ttH	qqtt	ggH
Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	✓		✓	✓				✓	
$pp \to t\bar{q}$	✓		✓	✓				✓	
$pp \to tW$	✓		✓	✓					
$pp \to t\bar{t}$	✓							✓	
$pp \to t\bar{t}\gamma$	✓	✓	✓					✓	
$pp \to t\gamma j$	✓	✓	✓	✓				✓	
$pp \to t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \to tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}W$	✓							✓	
$e^+e^- \to t\bar{t}$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}H$	✓						✓	✓	✓
$pp \to tHj$	✓		✓	✓			✓	✓	✓
$gg \to H, Hj, HZ$	✓			✓	✓	✓	✓		✓

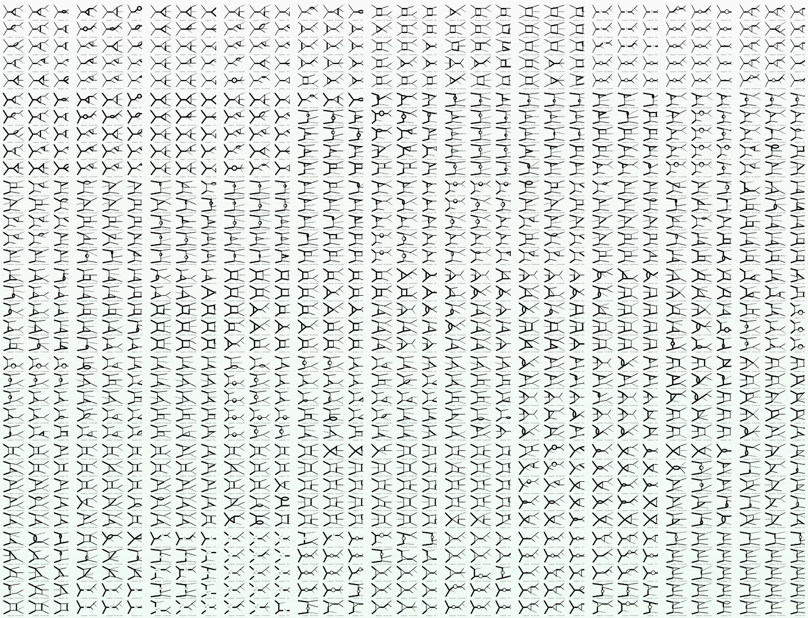
Coupling measurements

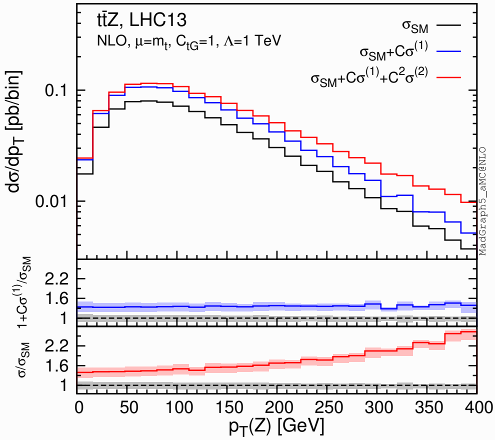
	tqZ/γ					tqg	tqH	lltq
Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to ql^+l^-$	✓	✓	✓	✓	✓	✓		✓
$t \to q\gamma$				✓	✓	✓		
$t \to qH$						✓	✓	
$pp \to t$						✓		
$pp \to tl^+l^-$	✓	✓	✓	✓	✓	✓		(✓)
$pp \to t\gamma$				✓	✓	✓		
$pp \to tH$						✓	✓	

FCNC searches

*color-neutral operators are free.

```
shell> ./bin/mg5
MG5_aMC> import model TopEFT
MG5_aMC> generate p p > t t~ Z EFT=1 [QCD]
MG5_aMC> output some_DIR
MG5_aMC> launch
```




tt̄Z, LHC13
NLO, μ=m$_t$, C$_{tG}$=1, Λ=1 TeV
σ$_{SM}$
σ$_{SM}$+Cσ$^{(1)}$
σ$_{SM}$+Cσ$^{(1)}$+C^{2}σ$^{(2)}$
dσ/dp$_T$ [pb/bin]
0.1
0.01
MadGraph5_aMC@NLO
1+Cσ$^{(1)}$/σ$_{SM}$
σ/σ$_{SM}$
2.2
1.6
1
0 50 100 150 200 250 300 350 400
p$_T$(Z) [GeV]

For more details, see. . .

Processes	Operators	Refs
FCNC production	$tqX,\ X=g,\gamma,Z,h$	[Degrande,Maltoni,Wang,CZ,'14]
$t\bar{t}$	chromo-dipole	[D.B.Franzosi,CZ,'15]
single t (s-&t-channel+tW)	tbW couplings	[CZ,'16]
ttZ,$tt\gamma$,($gg\to HZ$)	$ttX, X=Z,\gamma,g$	[O.B.Bylund et al,'16]
ttH	chromo, ggH, top Yukawa	[Vryonidou,Maltoni,CZ,'16]
$e^+e^-\to t\bar{t}$	ttX, 4-fermion	[G. Durieux,'17]
(Higgs production)	EW/Higgs	[C. Degrande et al.,'16]
$tHj, tZj, (t\gamma j)$	all above plus EW and Higgs plus 4-fermion	[C.Degrande et al.,'18]

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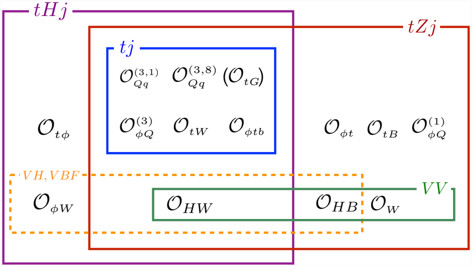
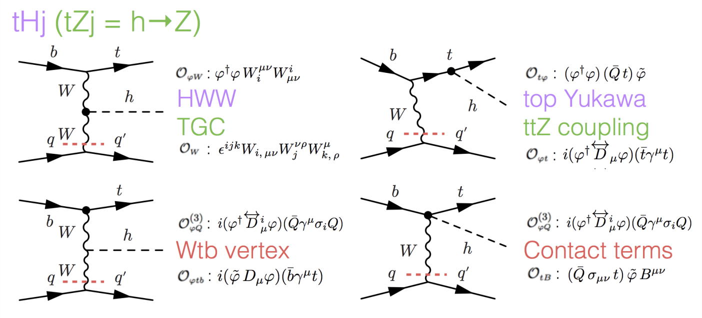
Single top with H/Z

- Involve top, W/Z, H.
  - Nice test for putting all available stuff together.



- Unitarity cancellations: announced sensitivity at high mass.

Single top with H/Z



- The *tXj* channels access the $2 \to 2$ sub-amplitudes, probe the energy dependence due to unitarity cancellation spoiled by BSM effects, and reveal the rich interplay between EFT operators from different sectors.
- See also *[Maltoni,Paul,Stelzer,Willenbrock,'01]*, *[Biswas,Gabrielli,Mele,12]*, *[Farina,Grojean,Maltoni,Salvioni,Thamm,'12]*, *[Demartin,Maltoni,Mawatari,Zaro,'15]*, *[Dror,Farina,Salvioni,Serra,'16]*.

Single top with H/Z: sub-amplitudes

$bW \to tH$ amplitude

$\lambda_b, \lambda_W, \lambda_t$	SM	$\mathcal{O}_{t\phi}$	$\mathcal{O}_{\phi Q}^{(3)}$	$\mathcal{O}_{\phi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{HW}$
$-, 0, -$	s^0	s^0	$\sqrt{s(s+t)}$	s^0	s^0	$\sqrt{s(s+t)}$
$-, 0, +$	$\frac{1}{\sqrt{s}}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$\frac{1}{\sqrt{s}}$	$\frac{m_W s}{\sqrt{-t}}$	$\frac{1}{\sqrt{s}}$
$-, -, -$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$	$m_W\sqrt{-t}$	$\frac{m_W s}{\sqrt{-t}}$	$m_t\sqrt{-t}$	$\frac{m_W(s+t)}{\sqrt{-t}}$
$-, -, +$	$\frac{1}{s}$	s^0	s^0	$-$	$\sqrt{s(s+t)}$	$\frac{1}{s}$
$-, +, -$	$\frac{1}{\sqrt{s}}$	$-$	$\frac{1}{\sqrt{s}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{1}{\sqrt{s}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$
$-, +, +$	s^0	$-$	s^0	s^0	s^0	$\frac{1}{s}$

$\mathcal{O}_{\phi tb}, \lambda_b = +$

λ_t \ λ_W	0	$+$	$-$
$+$	$\sqrt{s(s+t)}$	$m_W\sqrt{-t}$	$\frac{1}{\sqrt{s}}$
$-$	$m_t\sqrt{-t}$	s^0	s^0

$s \sim -t \gg v^2$

$bW \to tZ$ amplitude

$\lambda_b, \lambda_W, \lambda_t, \lambda_Z$	SM	$\mathcal{O}_{\phi Q}^{(3)}$	$\mathcal{O}_{\phi Q}^{(1)}$	$\mathcal{O}_{\phi t}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{W}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$
$-,0,-,0$	s^0	$\sqrt{s(s+t)}$	$-$	$-$	$-$	s^0	s^0	$\sqrt{s(s+t)}$	s^0
$-,0,+,0$	$\frac{1}{\sqrt{s}}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_Z\sqrt{-t}$	$\frac{m_W(2s+3t)}{\sqrt{-t}}$	$-$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$
$-,-,-,0$	$\frac{1}{\sqrt{s}}$	$m_W\sqrt{-t}$	$-$	$-$	$-$	$-$	$\frac{m_W(s+2t)}{\sqrt{-t}}$	$m_W\sqrt{-t}$	$\frac{1}{\sqrt{s}}$
$-,-,+,0$	$\frac{1}{s}$	s^0	s^0	s^0	s^0	$\sqrt{s(s+t)}$	s^0	s^0	$\frac{1}{\sqrt{s}}$
$-,0,-,-$	$\frac{1}{\sqrt{s}}$	$m_W\sqrt{-t}$	$-$	$-$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$\frac{m_W(s+2t)}{\sqrt{-t}}$	$\frac{m_W(s s_W^2+2t)}{\sqrt{-t}}$	$\frac{m_W s}{\sqrt{-t}}$
$-,0,-,+$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$
$-,0,+,-$	s^0	s^0	s^0	$-$	$-$	s^0	s^0	s^0	s^0
$-,0,+,+$	$\frac{1}{s}$	s^0	s^0	s^0	$\sqrt{s(s+t)}$	$\sqrt{s(s+t)}$	$-$	s^0	s^0
$-,+,-,0$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$
$-,+,+,0$	s^0	s^0	$-$	$-$	$-$	s^0	$-$	s^0	$\frac{1}{s}$
$-,-,-,-$	s^0	s^0	s^0	$-$	s^0	s^0	s^0	s^0	s^0
$-,-,-,+$	$\frac{1}{s}$	$-$	$-$	$-$	$-$	$-$	$\sqrt{s(s+t)}$	s^0	s^0
$-,-,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$\frac{m_Z\left(s_W^2 t-3c_W^2(2s+t)\right)}{\sqrt{-t}}$	$-$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$
$-,-,+,+$	$-$	$-$	$-$	$-$	$m_W\sqrt{-t}$	$m_Z\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$
$-,+,-,-$	$\frac{1}{s}$	$-$	$-$	$-$	$-$	$-$	$\sqrt{s(s+t)}$	s^0	s^0
$-,+,-,+$	s^0	s^0	s^0	$-$	$-$	$-$	$-$	s^0	s^0
$-,+,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$-$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$
$-,+,+,+$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$

$\mathcal{O}_{\phi tb},\ \lambda_b, \lambda_t = +,+$

λ_Z \ λ_W	0	$+$	$-$
0	$\sqrt{s(s+t)}$	$m_W\sqrt{-t}$	$-$
$+$	$m_Z\sqrt{-t}$	s^0	$-$
$-$	$-$	$-$	s^0

$\mathcal{O}_{\phi tb},\ \lambda_b, \lambda_t = +,-$

λ_Z \ λ_W	0	$+$	$-$
0	$-$	$-$	s^0
$+$	s^0	$-$	$-$
$-$	s^0	$-$	$-$

Inclusive results: *tHj*@13 TeV

- Parameterization:

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

- Large deviation $\gtrsim 1$ within current constraints (O_{tW} and $O_{t\varphi}$).
- K-factor not universal.
- Reduction of scale/PDF uncertainties.

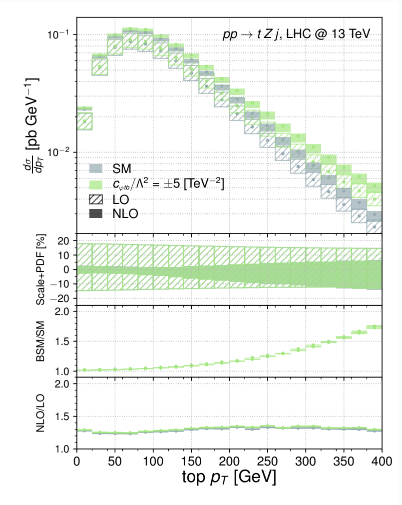
σ [fb]	LO	NLO	K-factor
σ_{SM}	$57.56(4)^{+11.2\%}_{-7.4\%} \pm 10.2\%$	$75.87(4)^{+2.2\%}_{-6.4\%} \pm 1.2\%$	1.32
$\sigma_{\phi W}$	$8.12(2)^{+13.1\%}_{-9.3\%} \pm 9.3\%$	$7.76(2)^{+7.0\%}_{-6.3\%} \pm 1.0\%$	0.96
$\sigma_{\phi W,\phi W}$	$5.212(7)^{+10.6\%}_{-6.8\%} \pm 10.2\%$	$6.263(7)^{+2.6\%}_{-7.8\%} \pm 1.3\%$	1.20
$\sigma_{t\phi}$	$-1.203(6)^{+12.0\%}_{-15.6\%} \pm 8.9\%$	$-0.246(6)^{+144.5[31.4]\%}_{-157.8[19.0]\%} \pm 2.1\%$	0.20
$\sigma_{t\phi,t\phi}$	$0.6682(9)^{+12.7\%}_{-8.9\%} \pm 9.6\%$	$0.7306(8)^{+4.6[0.6]\%}_{-7.3[0.2]\%} \pm 1.0\%$	1.09
σ_{tW}	$19.38(6)^{+13.0\%}_{-9.3\%} \pm 9.4\%$	$22.18(6)^{+3.8[0.4]\%}_{-6.8[0.9]\%} \pm 1.0\%$	1.14
$\sigma_{tW,tW}$	$46.40(8)^{+9.3\%}_{-5.5\%} \pm 11.1\%$	$71.24(8)^{+7.4[1.5]\%}_{-14.0[6.9]\%} \pm 1.9\%$	1.54
$\sigma_{\phi Q^{(3)}}$	$-3.03(3)^{+0.0\%}_{-2.2\%} \pm 15.4\%$	$-10.04(4)^{+11.1\%}_{-8.9\%} \pm 1.8\%$	3.31
$\sigma_{\phi Q^{(3)},\phi Q^{(3)}}$	$11.23(2)^{+9.4\%}_{-5.6\%} \pm 11.2\%$	$15.28(2)^{+5.0\%}_{-10.9\%} \pm 1.8\%$	1.36
$\sigma_{\phi tb}$	0	0	–
$\sigma_{\phi tb,\phi tb}$	$2.752(4)^{+9.4\%}_{-5.5\%} \pm 11.3\%$	$3.768(4)^{+5.0\%}_{-10.9\%} \pm 1.8\%$	1.54
σ_{HW}	$-3.526(4)^{+5.6\%}_{-9.5\%} \pm 10.9\%$	$-5.27(1)^{+6.5\%}_{-2.9\%} \pm 1.5\%$	1.50
$\sigma_{HW,HW}$	$0.9356(4)^{+7.9\%}_{-4.0\%} \pm 12.3\%$	$1.058(1)^{+4.8\%}_{-11.9\%} \pm 2.3\%$	1.13
σ_{tG}	$-0.418(5)^{+12.3\%}_{-9.8\%} \pm 1.1\%$		–
$\sigma_{tG,tG}$	$1.413(1)^{+21.3\%}_{-30.6\%} \pm 2.5\%$		–
$\sigma_{Qq^{(3,1)}}$	$-22.50(5)^{+8.0\%}_{-11.8\%} \pm 9.7\%$	$-20.10(5)^{+13.8\%}_{-13.3\%} \pm 1.1\%$	0.89
$\sigma_{Qq^{(3,1)},Qq^{(3,1)}}$	$69.78(3)^{+8.0\%}_{-4.1\%} \pm 12.1\%$	$62.20(3)^{+11.5\%}_{-15.9\%} \pm 2.3\%$	0.89
$\sigma_{Qq^{(3,8)}}$	–	$0.25(3)^{+25.4\%}_{-27.1\%} \pm 4.7\%$	–
$\sigma_{Qq^{(3,8)},Qq^{(3,8)}}$	$15.53(2)^{+8.0\%}_{-4.1\%} \pm 12.1\%$	$14.07(2)^{+11.0\%}_{-15.7\%} \pm 2.1\%$	0.91

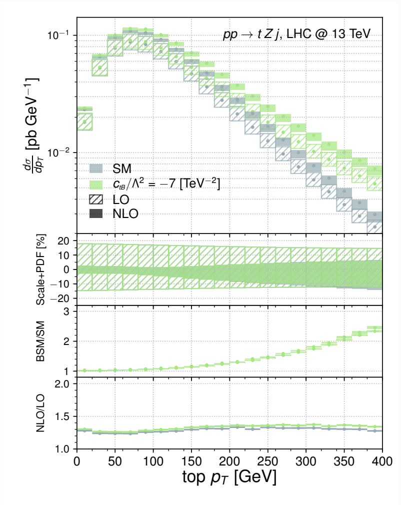
Inclusive results: tZj@13 TeV

- K-factor not universal.
- Reduction of scale/PDF uncertainties.
- Deviation $\sim 20\%$ within current constraints (O_{tW} and O_{tB}).
- EFT contributions smaller relative to SM.
    - Higgs always radiated from top/EW gauge boson, but Z boson can also come from light quark leg.

σ [fb]	LO	NLO	K-factor
σ_{SM}	$660.8(4)^{+13.7\%}_{-9.6\%} \pm 9.7\%$	$839.1(5)^{+1.1\%}_{-5.1\%} \pm 1.0\%$	1.27
σ_{W}	$-7.87(7)^{+8.4\%}_{-12.6\%} \pm 9.7\%$	$-8.77(8)^{+8.5\%}_{-4.3\%} \pm 1.1\%$	1.12
$\sigma_{W,W}$	$34.58(3)^{+8.2\%}_{-3.9\%} \pm 13.0\%$	$43.80(4)^{+6.6\%}_{-15.1\%} \pm 2.8\%$	1.27
σ_{tB}	$2.23(2)^{+14.7[0.9]\%}_{-10.7[1.0]\%} \pm 9.4\%$	$2.94(2)^{+2.3[0.4]\%}_{-3.0[0.7]\%} \pm 1.1\%$	1.32
$\sigma_{tB,tB}$	$2.833(2)^{+10.5[1.7]\%}_{-6.3[1.9]\%} \pm 11.1\%$	$4.155(3)^{+4.7[0.9]\%}_{-10.1[1.4]\%} \pm 1.7\%$	1.47
σ_{tW}	$2.66(4)^{+18.8[0.9]\%}_{-15.3[1.0]\%} \pm 11.4\%$	$13.0(1)^{+15.8[2.1]\%}_{-22.8[0.0]\%} \pm 1.2\%$	4.90
$\sigma_{tW,tW}$	$48.16(4)^{+10.0[1.7]\%}_{-5.8[1.9]\%} \pm 11.3\%$	$80.00(4)^{+7.9[1.3]\%}_{-14.7[1.6]\%} \pm 1.9\%$	1.66
$\sigma_{\phi dtR}$	$4.20(1)^{+14.9\%}_{-10.9\%} \pm 9.3\%$	$4.94(2)^{+3.4\%}_{-6.7\%} \pm 1.0\%$	1.18
$\sigma_{\phi dtR,\phi dtR}$	$0.3326(3)^{+13.6\%}_{-9.5\%} \pm 9.6\%$	$0.4402(5)^{+3.7\%}_{-9.3\%} \pm 1.0\%$	1.32
$\sigma_{\phi Q}$	$14.98(2)^{+14.5\%}_{-10.5\%} \pm 9.4\%$	$18.07(3)^{+2.3\%}_{-1.6\%} \pm 1.0\%$	1.21
$\sigma_{\phi Q,\phi Q}$	$0.7442(7)^{+14.1\%}_{-10.0\%} \pm 9.5\%$	$1.028(1)^{+2.8\%}_{-7.3\%} \pm 1.0\%$	1.38
$\sigma_{\phi Q^{(3)}}$	$130.04(8)^{+13.8\%}_{-9.8\%} \pm 9.5\%$	$161.4(1)^{+0.9\%}_{-4.8\%} \pm 1.0\%$	1.24
$\sigma_{\phi Q^{(3)},\phi Q^{(3)}}$	$17.82(2)^{+11.7\%}_{-7.5\%} \pm 10.5\%$	$23.98(2)^{+3.7\%}_{-9.3\%} \pm 1.4\%$	1.35
$\sigma_{\phi tb}$	0	0	–
$\sigma_{\phi tb,\phi tb}$	$2.949(2)^{+10.5\%}_{-6.2\%} \pm 11.1\%$	$4.154(4)^{+5.1\%}_{-11.2\%} \pm 1.8\%$	1.41
σ_{HW}	$-5.16(6)^{+7.8\%}_{-12.0\%} \pm 10.5\%$	$-6.88(8)^{+6.4\%}_{-2.0\%} \pm 1.4\%$	1.33
$\sigma_{HW,HW}$	$0.912(2)^{+9.4\%}_{-5.2\%} \pm 12.0\%$	$1.048(2)^{+5.2\%}_{-12.8\%} \pm 2.1\%$	1.15
σ_{HB}	$-3.015(9)^{+9.9\%}_{-13.9\%} \pm 9.5\%$	$-3.76(1)^{+5.2\%}_{-1.0\%} \pm 1.0\%$	1.25
$\sigma_{HB,HB}$	$0.02324(6)^{+12.7\%}_{-8.5\%} \pm 9.9\%$	$0.02893(6)^{+2.3\%}_{-7.5\%} \pm 1.1\%$	1.24
σ_{tG}	$0.45(2)^{+93.0\%}_{-148.8\%} \pm 4.9\%$		–
$\sigma_{tG,tG}$	$2.251(4)^{+20.9\%}_{-30.0\%} \pm 2.5\%$		–
$\sigma_{Qq^{(3,1)}}$	$-393.5(5)^{+8.1\%}_{-12.3\%} \pm 10.0\%$	$-498(1)^{+8.9\%}_{-3.2\%} \pm 1.2\%$	1.26
$\sigma_{Qq^{(3,1)},Qq^{(3,1)}}$	$462.25(3)^{+8.4\%}_{-4.1\%} \pm 12.7\%$	$545.50(5)^{+7.4\%}_{-17.4\%} \pm 2.9\%$	1.18
$\sigma_{Qq^{(3,8)}}$	0	$-0.9(3)^{+23.3\%}_{-26.3\%} \pm 19.2\%$	–
$\sigma_{Qq^{(3,8)},Qq^{(3,8)}}$	$102.73(5)^{+8.4\%}_{-4.1\%} \pm 12.7\%$	$111.18(5)^{+9.3\%}_{-18.4\%} \pm 2.8\%$	1.08

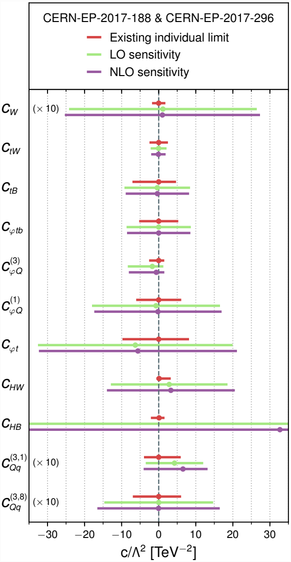
Differential: *tZj*@13 TeV



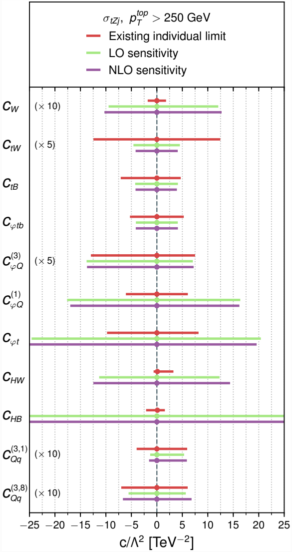


Potentially large deviation at the tails. . . (saturating current limits)

Current vs. future

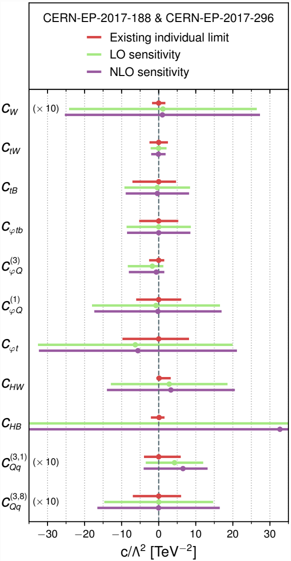


$\mu = 0.75 \pm 0.27$ & 1.31 ± 0.47



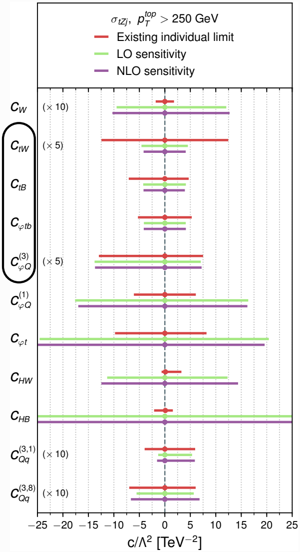
$p_T > 250$ GeV, assume 10x smaller xsec compensated by HL-LHC

Current vs. future



$\mu = 0.75 \pm 0.27$ & 1.31 ± 0.47

Expected from subamplitude behaviours



$p_T > 250$ GeV, assume 10x smaller xsec compensated by HL-LHC

Outline

1. EFT interpretation of top measurements
2. Top EFT @ NLO QCD
   - Why we need NLO
   - Available processes and operators
   - Single top plus H/Z
   - Future plan
3. EW corrections
   - Higgs production & decay
4. Summary

Towards full SMEFT @ NLO in QCD implementation

We have started to work on a more complete SMEFT implementation @ NLO in QCD, including all relevant OPs for **top, Higgs** and **EW** measurements.

Towards full SMEFT @ NLO in QCD implementation

With two-quark and Higgs/EW operators implemented, we are still missing:

- $f^{ABC}G_{\mu}^{A\nu}G_{\nu}^{B\rho}G_{\rho}^{C\mu}$
- Four-fermion operators.
- Processes where QCD EW orders are mixed.

The three gluon operator

- Multijet processes impose so far the best bounds.

  [F. Krauss,S. Kuttimalai,T. Plehn,'16]

- No interference with SM in di-jet at LO. *[Cho & Simmons '94]*
- NLO being checked. *(Hirschi, Tsinikos, Vryondiou,. . .)*

Towards full SMEFT @ NLO in QCD implementation

With two-quark and Higgs/EW operators implemented, we are still missing:

- $f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ ✓
- Four-fermion operators.
- Processes where QCD QED orders are mixed.

Four-fermion operator

- Main difficulty is the "evanescent operator" basis, which now becomes automated in NLOCT.

Four-fermion operators are important, as they are tree-level induced and enter many processes.

- Two-light-two-heavy *qqtt* operators are important for $t\bar{t}$ and $t\bar{t}+X$.
- *tttt* and *ttbb* production: rich phenomenology, more opportunities...

[Degrande,Gerard,Grojean,Maltoni,Servant,'10]

Four-top production

The four top production

- has a current upper bound about $4 \sim 5 \times$SM.
- ALREADY sensitive to *qqtt* operators.
- Resulting constraints can compete with $t\bar{t}$.

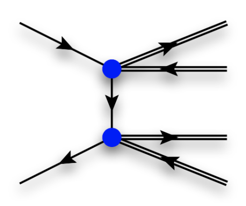
The special sensitivity comes from:

1. Large threshold energy.

$$C_{qqtt}\frac{E^2}{\Lambda^2} > 1$$

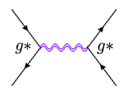
2. Multiple insertion.

$$\sigma_{dim-6} \sim \sigma_{SM}\left(C_{qqtt}\frac{E^2}{\Lambda^2}\right)^4$$



Is EFT@dim6 still valid with multiple insertion of operators, $\sim (CE^2/\Lambda^2)^4$?

- Consider the one-scale-one-coupling example in [Contino,Falkowski,Goertz,Grojean,Riva,'16]
- When the extra $1/\Lambda^2$ from expanding the amplitude:



$$\frac{1}{p^2-\Lambda_{NP}^2} = -\frac{1}{\Lambda_{NP}^2}\left[1+\frac{p^2}{\Lambda_{NP}^2}+\left(\frac{p^2}{\Lambda_{NP}^2}\right)^2+\ldots\right]$$

The expansion parameter is E^2/Λ_{NP}^2.
Valid as far as $p^2 < \Lambda_{NP}^2$ (by imposing kinematic cut), so neglecting dim-8 operator is ok, independent of size of $g*$.

- When the extra $1/\Lambda^2$ from squaring the amplitude:

$$M \sim g_{SM}^2 + \frac{g_*^2 E^2}{\Lambda_{NP}^2} \sim 1 + \frac{CE^2}{\Lambda^2}, \qquad (\text{using } \frac{g_*^2}{\Lambda_{NP}^2} = \frac{C}{\Lambda^2})$$

$$|M|^2 \sim g_{SM}^4 + \frac{g_{SM}^2 g_*^2 E^2}{\Lambda_{NP}^2} + \frac{g_*^4 E^4}{\Lambda_{NP}^4} \sim 1 + \frac{CE^2}{\Lambda^2} + \left(\frac{CE^2}{\Lambda^2}\right)^2$$

"Expansion parameter" is CE^2/Λ^2. it depends on g_* and if large, cannot truncate. But we can always include this term, as it does not involve dim-8 and higher operators.

Similar in four-top: $\sigma_{dim-6} \sim \sigma_{SM} \left(C^{(6)} \frac{E^2}{\Lambda^2} \right)^4$

- For multiple insertion and squaring amplitude, expansion paraemeter is

$$C^{(6)} E^2/\Lambda^2$$

  These will be kept. (Highest power is 4)

- For higher dim operators, if the expansion parameter is

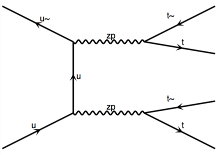
$$E^2/\Lambda_{NP}^2$$

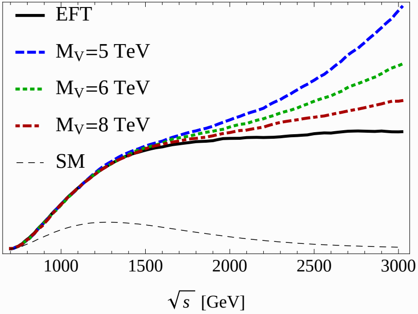
  we impose kinematic cut so that

$$E^2 < M_{cut}^2 < \Lambda_{NP}^2$$

  - Could be model dependent, but is natural for "one-scale-one-coupling" kind of models. (Also process-dependent: four-top will not enhanced by more than four powers of g_*.)

Example

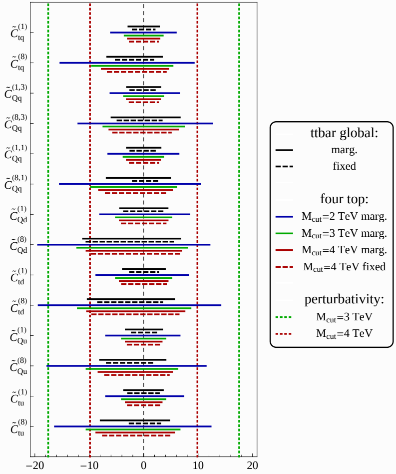




Comparison with $t\bar{t}$

- Four top projection: $\mu < 1.87$ with 300 fb^{-1}.
- Compared with $t\bar{t}$: global fit including
  - xsec at Tevatron + LHC 8/13
  - A_{FB} and A_C at Tevatron + LHC 8
  - m_{tt} distribution at LHC 8
- Maginalized limits on *qqtt* (also marginalized over *tttt* operators).
- Still conservative: assume SM signal shape, and compare M_{cut} with total upper limit.

[CZ,'17]

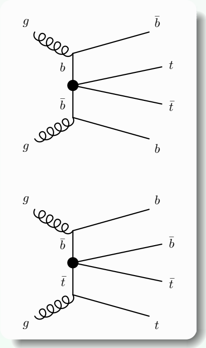


More to be probed with $pp \to ttbb$ (PRELIMINARY)

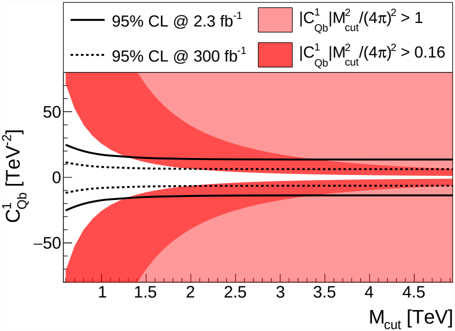
[J. D'Hondt, A. Mariotti, K. Mimasu, S. Moortgat, **CZ**, in progress]

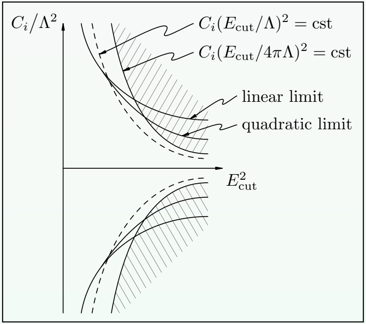
- $\sim 10\times$ larger cross section; kinematic information accessible.
- Lower threshold $\Rightarrow$ smaller M_{cut} $\Rightarrow$ more model-independence.
- Probe more 4-heavy operators:

$$
\begin{aligned}
O^1_{QQ} &= \frac{1}{2}\,(\bar{Q}\,\gamma_\mu\,Q)\,(\bar{Q}\,\gamma^\mu\,Q)\,,\\
O^8_{QQ} &= \frac{1}{2}\left(\bar{Q}\,\gamma_\mu\,T^A\,Q\right)\left(\bar{Q}\,\gamma^\mu\,T^A\,Q\right),\\
O^1_{tb} &= (\bar{t}\,\gamma_\mu\,t)\,(\bar{b}\,\gamma_\mu\,b)\,,\\
O^8_{tb} &= \left(\bar{t}\,\gamma_\mu T^A\,t\right)\left(\bar{b}\,\gamma_\mu\,T^A\,b\right),\\
O^1_{Qt} &= (\bar{Q}\,\gamma_\mu\,Q)\,(\bar{t}\,\gamma^\mu\,t)\,,\\
O^8_{Qt} &= \left(\bar{Q}\,\gamma_\mu\,T^A\,Q\right)\left(\bar{t}\,\gamma^\mu\,T^A\,t\right),\\
O^1_{Qb} &= (\bar{Q}\,\gamma_\mu\,Q)\,(\bar{b}\,\gamma^\mu\,b)\,,\\
O^8_{Qb} &= \left(\bar{Q}\,\gamma_\mu\,T^A\,Q\right)\left(\bar{b}\,\gamma^\mu\,T^A\,b\right),\\
O^1_{QtQb} &= (\bar{Q}\,t)\,\varepsilon\,(\bar{Q}\,b)\,,\\
O^8_{QtQb} &= \left(\bar{Q}\,T^A\,t\right)\varepsilon\left(\bar{Q}\,T^A\,b\right).
\end{aligned}
$$



Validity & perturbativity (PRELIMINARY)



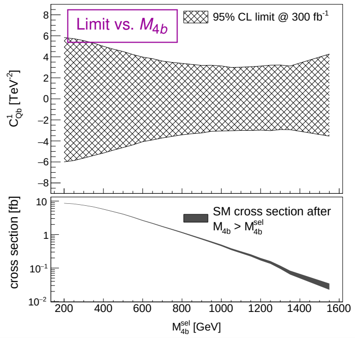


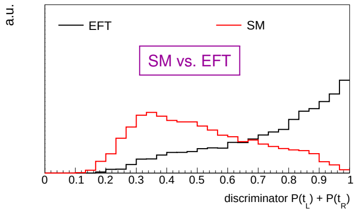
Limits at 95% CL on C^1_{Qb} as a function of the mass cut M_{cut} for an integrated luminosity of 2.3 fb^{-1} (solid line) and 300 fb^{-1} (dashed line). The non-perturbative regime of the EFT in which $|C|M^2_{cut}/\Lambda^2 < (4\pi)^2$ is indicated with the light red shaded region. The darker red region represents the extension of the non-perturbative region for which the upper limit on the Wilson coefficient (at 300 fb^{-1}) crosses exactly the perturbativity threshold at a mass cut of M_{cut} = 2 TeV

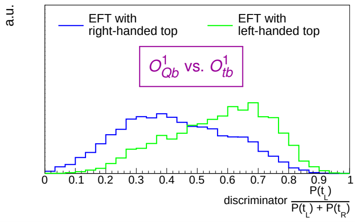
Approach (PRELIMINARY)

To improve sensitivity:

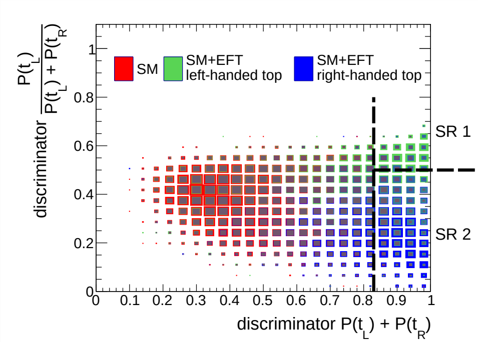
- Kinematic cut on M_{4b} ⇓
- Use a multi-class shallow neural network ⇒

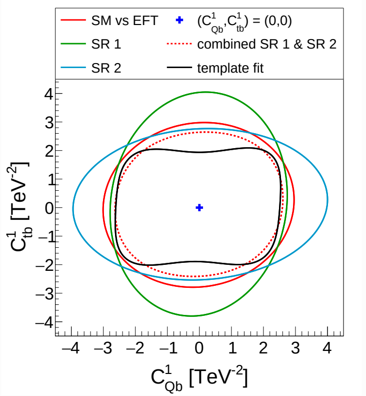




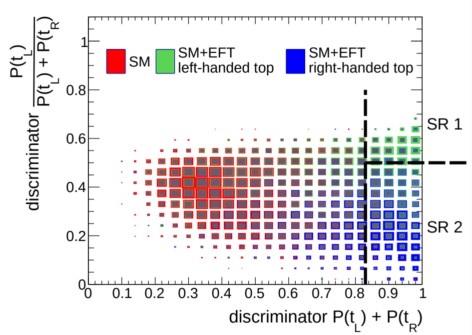


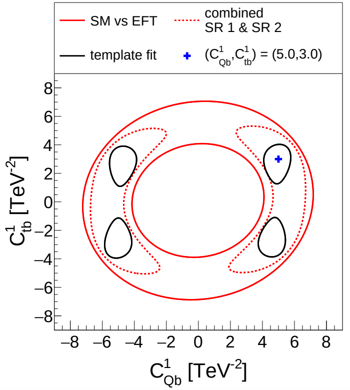
NN outputs (PRELIMINARY)





NN outputs (PRELIMINARY)





Towards full SMEFT @ NLO in QCD implementation

With two-quark and Higgs/EW operators implemented, we are still missing:

- $f^{ABC} G_{\mu}^{A\nu} G_{\nu}^{B\rho} G_{\rho}^{C\mu}$ ✓
- Four-quark operators. Being worked out
- Processes where QCD QED orders are mixed.

Towards full SMEFT @ NLO in QCD implementation

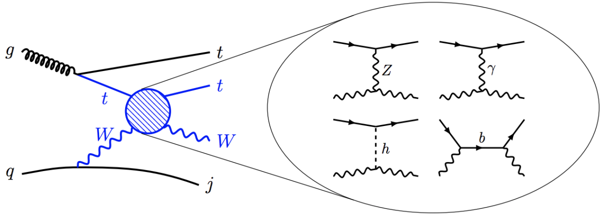


Figure 1: $tW \to tW$ scattering at the LHC. For definiteness, in the inset we show the diagrams corresponding to $tW^- \to tW^-$.

[Dror,Farina,Salvioni,Serra,'16]

Outline

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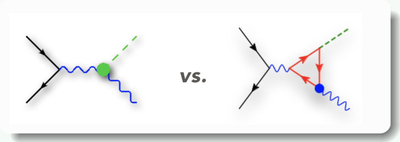
Why EW?

[E. Vryonidou and **CZ**, '18]

In particular, focus on top-loop induced contributions.

- When saying "Higgs couplings", what are we really talking about?



- Potentially, large relative corrections (unlike in the SM).

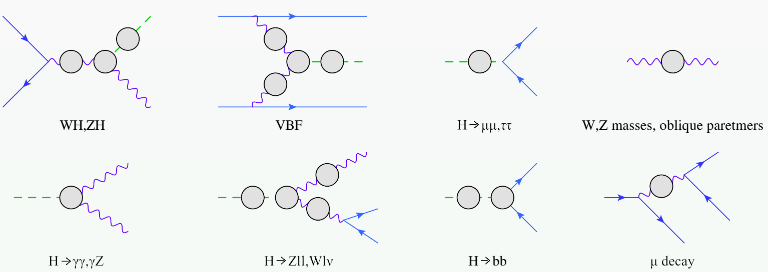
$$\frac{\sigma_{loop}}{\sigma_{tree}} \sim \alpha_{EW} \frac{C_{top}}{C_{Higgs}}$$

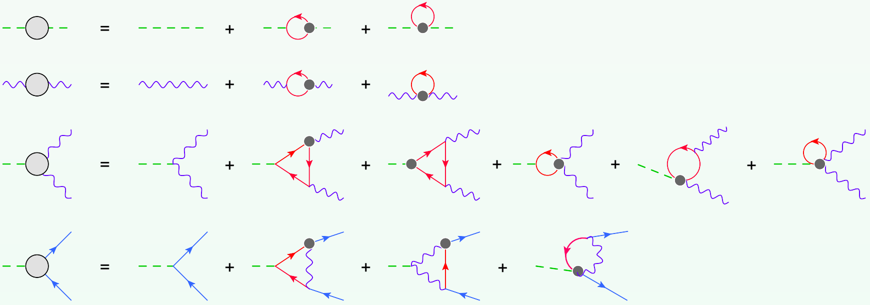
given that top operator constraints are in general much weaker.

- All Higgs production & decay are affected by same effects.

- A first step towards extending the existing NLO SMEFT implementation to incorporating EW corrections.
  - Some NLO EW results for Higgs decay, e.g. [Hartmann & Trott, '15], [Ghezzi et al., '15], [Gauld et al., '16], [Dawson & Giardino, '18]

- EW top-loop contribution in Higgs processes is a suitable starting point.


WH,ZH
VBF
H→μμ,ττ
W,Z masses, oblique paretmers
H→γγ,γZ
H→Zll,Wlν
H→bb
μ decay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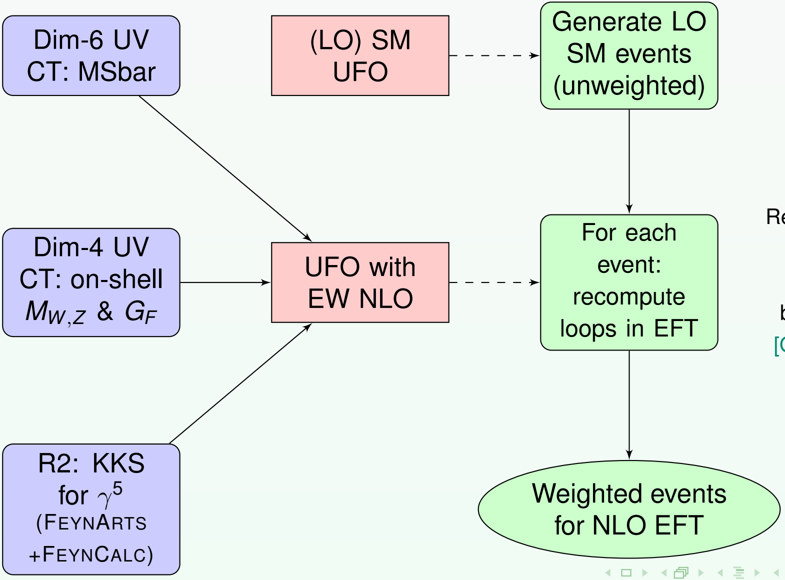
+

How it works (for now)



Reweighting module of MG5 based on [Oliver, '16]

Operator set

- "Top operators" (top-gauge/top-Higgs couplings)

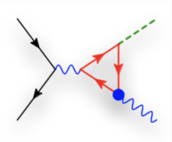
$$O_{t\varphi} = \bar{Q}t\tilde{\varphi}\,(\varphi^\dagger\varphi) + h.c.,\qquad O_{\varphi Q}^{(1)} = \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q),$$

$$O_{\varphi Q}^{(3)} = \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q),\qquad O_{\varphi t} = \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t),$$

$$O_{\varphi tb} = (\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{t}\gamma^\mu b) + h.c.,\qquad O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\,\tilde{\varphi}W^I_{\mu\nu} + h.c.,$$

$$O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\,\tilde{\varphi}B_{\mu\nu} + h.c.,$$

$$O_{\varphi Q}^{(+)} \equiv \frac{1}{2}\left(O_{\varphi Q}^{(1)} + O_{\varphi Q}^{(3)}\right),\qquad O_{\varphi Q}^{(-)} \equiv \frac{1}{2}\left(O_{\varphi Q}^{(1)} - O_{\varphi Q}^{(3)}\right).$$



- "Higgs operators"

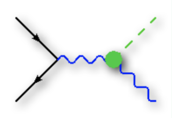
$$O_{\varphi WB} = \varphi^\dagger\tau^I\varphi W^I_{\mu\nu}B^{\mu\nu},\qquad O_{\varphi W} = \varphi^\dagger\varphi W^I_{\mu\nu}W^{I\mu\nu},$$

$$O_{\varphi B} = \varphi^\dagger\varphi B_{\mu\nu}B^{\mu\nu},\qquad O_{\varphi\Box} = \left(\varphi^\dagger\varphi\right)\Box\left(\varphi^\dagger\varphi\right),$$

$$O_{\varphi D} = \left(\varphi^\dagger D^\mu\varphi\right)^*\left(\varphi^\dagger D_\mu\varphi\right),\qquad O_W = iD^\mu\varphi^\dagger\tau^I D^\nu\varphi W^I_{\mu\nu},$$

$$O_B = iD^\mu\varphi^\dagger D^\nu\varphi B_{\mu\nu},\qquad O_{b\varphi} = (\varphi^\dagger\varphi)\bar{Q}b\varphi,$$

$$O_{\mu\varphi} = (\varphi^\dagger\varphi)\bar{l}_2 e_2\varphi,\qquad O_{\tau\varphi} = (\varphi^\dagger\varphi)\bar{l}_3 e_3\varphi.$$



RG mixing

	$O_{\varphi t}$	$O_{\varphi Q}^{(+)}$	$O_{\varphi Q}^{(-)}$	$O_{\varphi tb}$	O_{tW}	O_{tB}	$O_{t\varphi}$
$O_{\varphi WB}$	$\frac{1}{3s_W c_W}$	$\frac{1}{3s_W c_W}$	$-\frac{1}{6s_W c_W}$	0	$-\frac{5y_t}{2ec_W}$	$-\frac{3y_t}{2es_W}$	0
$O_{\varphi D}$	$-6\frac{y_t^2}{e^2}$	$3\frac{y_t^2-y_b^2}{e^2}$	$3\frac{y_t^2-y_b^2}{e^2}$	$-6\frac{y_t y_b}{e^2}$	0	0	0
$O_{\varphi\Box}$	$-\frac{3}{2}\frac{y_t^2}{e^2}$	$-\frac{3y_t^2+6y_b^2}{2e^2}$	$\frac{6y_t^2+3y_b^2}{2e^2}$	$3\frac{y_t y_b}{e^2}$	0	0	0
$O_{\varphi W}$	0	$\frac{1}{4s_W^2}$	$-\frac{1}{4s_W^2}$	0	$\frac{3y_t}{2es_W}$	0	0
$O_{\varphi B}$	$\frac{1}{3c_W^2}$	$\frac{1}{12c_W^2}$	$\frac{1}{12c_W^2}$	0	0	$\frac{5y_t}{2ec_W}$	0
O_W	0	$\frac{1}{es_W}$	$-\frac{1}{es_W}$	0	0	0	0
O_B	$\frac{4}{3ec_W}$	$\frac{1}{3ec_W}$	$\frac{1}{3ec_W}$	0	0	0	0
$O_{b\varphi}$	0	$-\frac{y_b}{2c_W^2} + y_b\frac{8\lambda-3y_t^2-5y_b^2}{4e^2}$	$y_b\frac{-4\lambda+3y_t^2+7y_b^2}{4e^2}$	$\frac{3y_t}{4s_W^2} - y_t\frac{2\lambda+y_t^2-6y_b^2}{2e^2}$	$\frac{y_t y_b}{2es_W}$	0	$\frac{3y_t y_b}{4e^2}$
$O_{\mu\varphi}$	0	$-\frac{3y_\mu(y_t^2+y_b^2)}{2e^2}$	$\frac{3y_\mu(y_t^2+y_b^2)}{2e^2}$	$\frac{3y_t y_b y_\mu}{e^2}$	0	0	$\frac{3y_t y_\mu}{2e^2}$
$O_{\tau\varphi}$	0	$-\frac{3y_\tau(y_t^2+y_b^2)}{2e^2}$	$\frac{3y_\tau(y_t^2+y_b^2)}{2e^2}$	$\frac{3y_t y_b y_\tau}{e^2}$	0	0	$\frac{3y_t y_\tau}{2e^2}$

Consistent with [Alonso, Jenkins, Manohar, Trott]

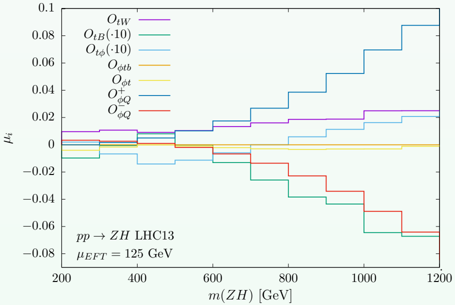
Renormalization

- Dim-6 coefficients are subtracted by MSbar, except for $C_{\varphi WB}$ and $C_{\varphi D}$, which enter precision EW measurements.
- We use S and T parameters as "observables" to renormalize $C_{\varphi WB}$ and $C_{\varphi D}$.
  - so that $C_{\varphi WB} = C_{\varphi D} = 0$ is consistent with EWPO.
  - In some sense, this means we always turn on top-operators in such a way that is consistent with the most stringent constraints from EWPO.
- Remaining dim-6 effects are subtracted with SM counter terms, in M_W, M_Z and G_F scheme.
  - In particular we want to fix M_W because it enters the phase space.

NLO EW UFO

with which we can simulate dim-6 top loop corrections in many processes thanks to automation

- at LHC: WH, ZH, VBF
- at e^+e^-: ZH, WWF, ZZF
- H decay: $\gamma\gamma$, γZ, $Wl\nu$, Zll, bb, $\tau\tau$, $\mu\mu$
- Many others: W/Z-pole, widths, $ee \to ff$, Drell-Yan,...
- Easy access to kinematic information.



Result 1: LHC

Within the current constraints, by how much can top operators affect Higgs signal strengths at the LHC?

	$\gamma\gamma$	γZ	bb	WW*	ZZ*	$\tau\tau$, $\mu\mu$
gg	(-100%,1980%)	(-88%,200%)	(-40%,48%)	(-40%,47%)	(-40%,46%)	(-40%,48%)
VBF	(-100%,1880%)	(-88%,170%)	(-6.1%,5.3%)	(-6.8%,6.7%)	(-8.8%,9.2%)	(-6.2%,5.9%)
WH	(-100%,1880%)	(-88%,170%)	(-5.5%,4.2%)	(-6.1%,5.6%)	(-7.8%,7.9%)	(-5.8%,5.1%)
ZH	(-100%,1880%)	(-87%,170%)	(-6.5%,5.9%)	(-7.1%,7.1%)	(-9.4%,9.9%)	(-6.8%,6.7%)

- Large in first two columns and first row, because SM is loop.
- The other pure NLO EW EFT effects are not negligible, $\sim 10\%$.

Result 2: future e^+e^- machine

- 250 GeV, with all top operators.

	$\gamma\gamma$	γZ	bb	WW*	ZZ*	$\tau\tau$, $\mu\mu$
ZH(+30%,-80%)	(-100%,1900%)	(-87%,160%)	(-7.5%,7.5%)	(-8.3%,8.6%)	(-11%,11%)	(-8%,8.3%)
ZH(-30%,+80%)	(-100%,1870%)	(-88%,180%)	(-7.6%,7.1%)	(-8.1%,7.9%)	(-10%,11%)	(-7.6%,7.3%)
WWF(+30%,-80%)	(-100%,1880%)	(-88%,170%)	(-5.7%,4.7%)	(-6.5%,6.2%)	(-8.1%,8.3%)	(-5.9%,5.3%)
WWF(-30%,+80%)	(-100%,1880%)	(-88%,170%)	(-5.7%,4.7%)	(-6.5%,6.2%)	(-8.1%,8.3%)	(-5.9%,5.3%)
ZZF(+30%,-80%)	(-100%,1790%)	(-88%,180%)	(-11%,8.6%)	(-11%,9.6%)	(-13%,12%)	(-11%,9%)
ZZF(-30%,+80%)	(-100%,1730%)	(-88%,180%)	(-14%,11%)	(-14%,12%)	(-15%,15%)	(-14%,11%)

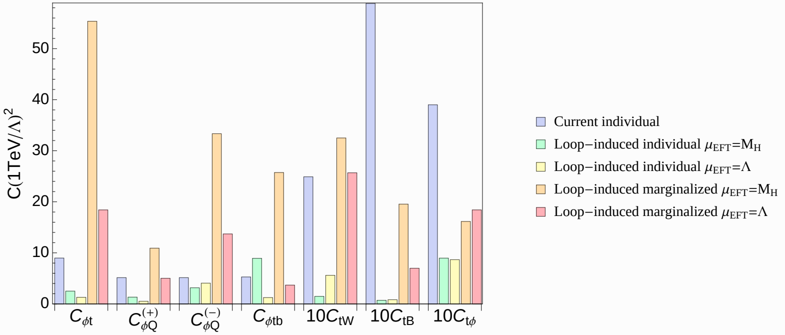
- 250 GeV, with only top Yukawa.

	$\gamma\gamma$	γZ	bb	WW*	ZZ*	$\tau\tau$, $\mu\mu$
ZH(+30%,-80%)	(-17%,19%)	(-7.3%,7%)	(-4%,3.3%)	(-4.5%,4%)	(-4.9%,4.4%)	(-3.6%,3%)
ZH(-30%,+80%)	(-17%,19%)	(-7.5%,7.2%)	(-4.1%,3.5%)	(-4.7%,4.2%)	(-5.1%,4.6%)	(-3.8%,3.2%)
WWF(+30%,-80%)	(-17%,18%)	(-7.2%,7%)	(-3.9%,3.3%)	(-4.4%,3.9%)	(-4.9%,4.3%)	(-3.5%,2.9%)
WWF(-30%,+80%)	(-17%,18%)	(-7.2%,7%)	(-3.9%,3.3%)	(-4.4%,3.9%)	(-4.9%,4.3%)	(-3.5%,2.9%)
ZZF(+30%,-80%)	(-17%,19%)	(-7.6%,7.3%)	(-4.2%,3.6%)	(-4.8%,4.3%)	(-5.2%,4.7%)	(-3.9%,3.3%)
ZZF(-30%,+80%)	(-17%,19%)	(-7.5%,7.2%)	(-4.1%,3.5%)	(-4.7%,4.2%)	(-5.1%,4.6%)	(-3.8%,3.2%)

It is possible to probe top couplings below the $t\bar{t}$ threshold

Result 3: HL-LHC

Projected “bounds” at HL-LHC



- Neglecting Higgs operators, only a “sensitivity” study.
- $\mu_{EFT} = M_H$: scale at the measurements. This is what should be done for a global fit.
- $\mu_{EFT} = \Lambda = 1$ TeV: scale at BSM scale. In general better limits but more model-dependent.

Take-home message?

- Treating the dim-6 top-quark sector (top EFT) and the Higgs/EW sector (Higgs EFT) separately will not continue to be a good approximation in the future.
- A more global approach will be needed to take into account the interplay at loop level.

Outline

1. EFT interpretation of top measurements
2. Top EFT @ NLO QCD
   - Why we need NLO
   - Available processes and operators
   - Single top plus H/Z
   - Future plan
3. EW corrections
   - Higgs production & decay
4. Summary

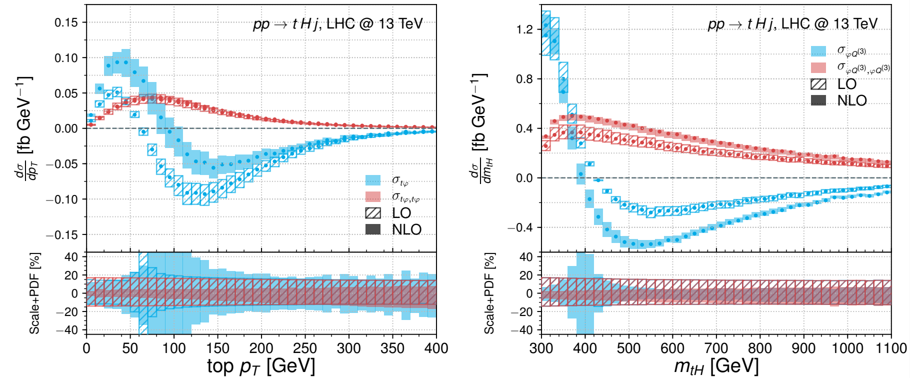
Summary

- Reasoning for higher orders in SMEFT.
- NLO QCD tools are available many processes and are becoming more complete.
- EW corrections are being studies, and can have non trivial implications.
- Let us know your needs.

Backups

Inclusive results: *tHj*@13 TeV

Phase space cancellation



Cancellations over the PS appear/disappear for the interference lead to strange K-factors and large scale uncertainties.

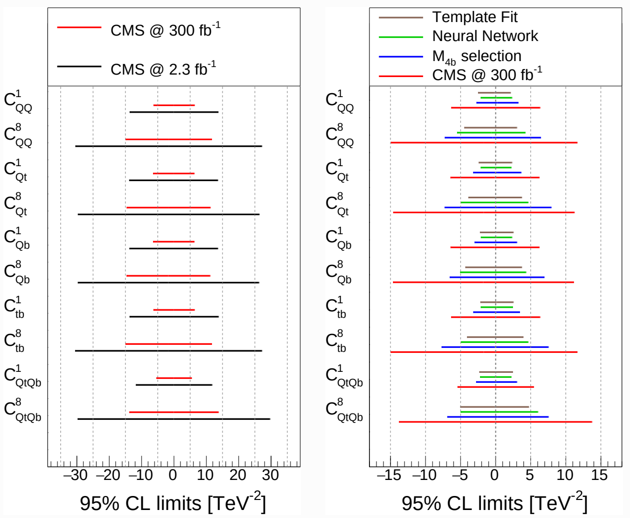
Sensitivities

	tj	tj ($p_T^t > 350$ GeV)	tZj	tZj ($p_T^t > 250$ GeV)	tHj
σ_{SM}	224 pb	880 fb	839 fb	69 fb	75.9 fb
r_{tW}	0.0275	0.024	0.016	0.010	0.292
$r_{tW,tW}$	0.0162	0.35	0.095	0.67	0.940
$r_{\varphi Q^{(3)}}$	0.1213	0.120	0.192	0.172	-0.132
$r_{\varphi Q^{(3)},\varphi Q^{(3)}}$	0.00368	0.0036	0.029	0.114	0.21
$r_{\varphi tb,\varphi tb}$	0.00090	0.0008	0.0050	0.027	0.050
r_{tG}	0.0003	-0.01	0.00053	-0.0048	-0.0055
$r_{tG,tG}$	0.00062	0.045	0.0027	0.022	0.025
$r_{Qq^{(3,1)}}$	-0.353	-4.4	-0.59	-2.22	-0.39
$r_{Qq^{(3,1)},Qq^{(3,1)}}$	0.126	11.5	0.65	5.1	1.21
$r_{Qq^{(3,8)},Qq^{(3,8)}}$	0.0308	2.73	0.133	1.01	1.08

Table 6: Comparison among the NLO sensitivities of tj (inclusive and with $p_T^t > 350$ GeV), tZj (inclusive and with $p_T^t > 250$ GeV), and tHj to the six operators which are common to the three processes, *i.e.*, those entering in tj. The interference term $r_i = \sigma_i/\sigma_{SM}$ (when non-zero) and the square $r_{i,i} = \sigma_{i,i}/\sigma_{SM}$ are given for each operator. σ_i and $\sigma_{i,i}$ are defined in Eq. (4.1).

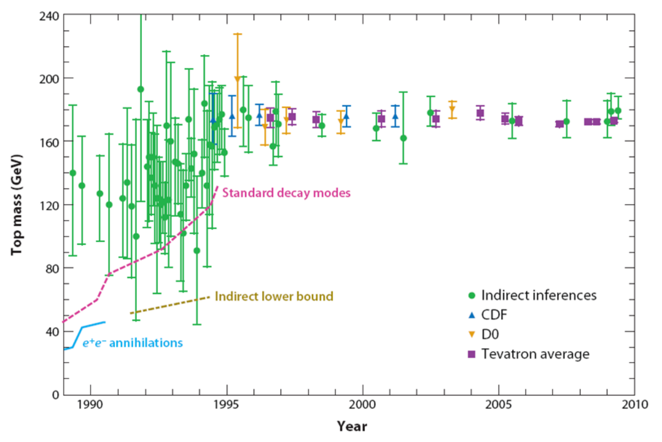
Prospects

- 95% CL on all the Wilson coefficients.
- Left: xsec measurement at 2.3 fb^{-1} and propects for 300 fb^{-1}.
- Right: xsec at 300 fb^{-1} compared with M_{4b} selection and NN.



Constrain the Top using PEWD

History of top quark mass



Quigg

Constrain the Top using EWPO

Top decay vs **Precision EW**

$$O_{tW} = \left(\bar{Q}\sigma^{\mu\nu}\tau^{I}t\right) W^{I}_{\mu\nu}$$

Direct probe:

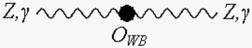
- Pros: Larger (LO) effect
- Cons: Larger background

Precision EW:

- Pros: Better precision level
- Cons: Loop suppressed effect

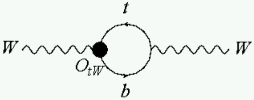
Need global fit

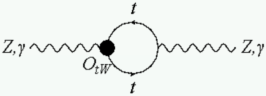
tree level:



$$O_{WB} = (\varphi^\dagger \tau^I \varphi)\, W^I_{\mu\nu} B^{\mu\nu}$$

loop level:





- with Dimensional Regularization and $\overline{MS}$

$$\alpha S = 4\frac{C_{WB}(\mu)v^2}{\Lambda^2} s_W c_W$$
$$+ N_c \frac{C_{tW}}{2\pi^2}\frac{\sqrt{2}m_W m_t}{\Lambda^2}\frac{5}{3}s_W^2\left(-\ln\frac{m_t^2}{\mu^2} - 2\frac{\sqrt{4m_t^2 - m_Z^2}}{m_Z}\arctan\frac{m_Z}{\sqrt{4m_t^2 - m_Z^2}} + 2\right)$$

…cannot distinguish C_{tW} from C_{WB} and set bound.

should avoid setting $C_{WB}(\mu) = 0$

Global Fit

However, if global:

- Include all 8 (t,b) operators at loop level.

$$
\begin{aligned}
O_{\phi Q}^{(3)} &= i(\phi^\dagger \tau^I D_\mu \phi)(\bar{Q}\gamma^\mu \tau^I Q), & O_{\phi Q}^{(1)} &= i(\phi^\dagger D_\mu \phi)(\bar{Q}\gamma^\mu Q), \\
O_{\phi t} &= i(\phi^\dagger D_\mu \phi)(\bar{t}\gamma^\mu t), & O_{\phi b} &= i(\phi^\dagger D_\mu \phi)(\bar{b}\gamma^\mu b), \\
O_{tW} &= (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W_{\mu\nu}^I, & O_{bW} &= (\bar{Q}\sigma^{\mu\nu}\tau^I b)\phi W_{\mu\nu}^I, \\
O_{tB} &= (\bar{Q}\sigma^{\mu\nu} t)\tilde{\phi} B_{\mu\nu}, & O_{bB} &= (\bar{Q}\sigma^{\mu\nu} b)\phi B_{\mu\nu}.
\end{aligned}
$$

- Include tree level EW operators.

$$
O_{WB} = \left(\varphi^\dagger \tau^I \varphi\right) W_{\mu\nu}^I B^{\mu\nu}, \quad O_{\varphi}^{(3)} = (\varphi^\dagger D^\mu \varphi)[(D_\mu \varphi)^\dagger \varphi].
$$

Correspond to S and T parameters.

- Include the full set of precision measurements (101 data points...)
- Enough d.o.f to constrain all!

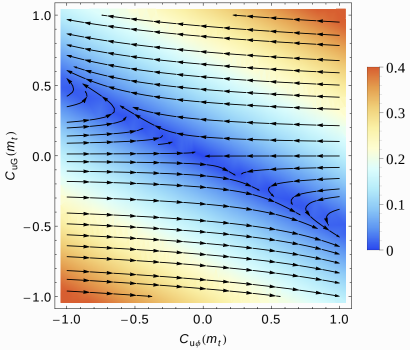
$$
\begin{pmatrix}
-0.702 & -0.701 & -0.000 & +0.128 & -0.003 & +0.000 & -0.000 & -0.000 \\
+0.094 & +0.087 & +0.002 & +0.992 & +0.019 & -0.001 & +0.001 & +0.000 \\
-0.244 & +0.251 & -0.228 & +0.019 & -0.901 & +0.071 & -0.080 & -0.041 \\
+0.405 & -0.404 & +0.675 & +0.004 & -0.408 & +0.049 & +0.218 & -0.005 \\
-0.136 & +0.136 & -0.126 & +0.000 & +0.002 & -0.138 & +0.936 & +0.229 \\
-0.035 & +0.034 & -0.039 & -0.001 & +0.094 & +0.745 & +0.244 & -0.610 \\
-0.004 & +0.004 & +0.007 & -0.000 & +0.025 & +0.646 & -0.090 & +0.757 \\
-0.505 & +0.505 & +0.689 & +0.000 & +0.108 & -0.014 & -0.054 & -0.009
\end{pmatrix}
\times \frac{1}{\Lambda^2}
\begin{pmatrix}
C_{\phi Q}^{(3)} \\ C_{\phi Q}^{(1)} \\ C_{\phi t} \\ C_{\phi b} \\ C_{tW} \\ C_{bW} \\ C_{tB} \\ C_{bB}
\end{pmatrix}
=
\begin{pmatrix}
-0.011 & \pm 0.014 \\
-0.59 & \pm 0.27 \\
+0.04 & \pm 1.17 \\
+2.84 & \pm 2.12 \\
+1.7 & \pm 11.9 \\
+8.7 & \pm 21.2 \\
+102.4 & \pm 50.4 \\
+1.10\text{e}+3 & \pm 1.41\text{e}+3
\end{pmatrix}
\text{TeV}^{-2}.
$$

Counting

- 3045 operators at dim-6 already
- 44807 at dim-8, 2092441 at dim-10, . . . , and at dim-15 everyone gets an operator. . .
  [Buchmuller & Wyler, '86] [B. Grzadkowski et al., '10] [Lehman & Marin, '15] [B. Henning et al., '15]
- Even in top physics, 4-fermion operators count 572 in total.

Example in $t \to uh$

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: $C_{uG}^{(13)} = 0.98$, $C_{u\varphi}^{(13)} = 0.23$

Single top with H/Z: operators

tHj

tZj

both

Rescaling of h couplings

NLO

$\mathcal{O}_W$	$\varepsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{Q}\gamma^\mu \tau^I Q) + \text{h.c.}$
$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W^{\mu\nu}_I W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\gamma^\mu Q) + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi) B^{\mu\nu} W^I_{\mu\nu}$	$\mathcal{O}_{\varphi t}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t) + \text{h.c.}$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$	$\mathcal{O}_{\varphi tb}$	$i(\tilde{\varphi} D_\mu \varphi)(\bar{t}\gamma^\mu b) + \text{h.c.}$
$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}^{(1)}_{\varphi q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}_i\gamma^\mu q_i) + \text{h.c.}$
$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q} t \tilde{\varphi} + \text{h.c.}$	$\mathcal{O}^{(3)}_{\varphi q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{q}_i\gamma^\mu \tau^I q_i) + \text{h.c.}$
$\mathcal{O}_{tW}$	$i(\bar{Q}\sigma^{\mu\nu}\tau_I t)\tilde{\varphi} W^I_{\mu\nu} + \text{h.c.}$	$\mathcal{O}_{\varphi u}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{u}_i\gamma^\mu u_i) + \text{h.c.}$
$\mathcal{O}_{tB}$	$i(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu} + \text{h.c.}$	$\mathcal{O}^{(3,1)}_{Qq}$	$(\bar{q}_i\gamma_\mu \tau_I q_i)(\bar{Q}\gamma^\mu \tau^I Q)$
$\mathcal{O}^{*}_{tG}$	$i(\bar{Q}\sigma^{\mu\nu} T_A t)\tilde{\varphi} G^A_{\mu\nu} + \text{h.c.}$	$\mathcal{O}^{(3,8)}_{Qq}$	$(\bar{q}_i\gamma_\mu \tau_I T_A q_i)(\bar{Q}\gamma^\mu \tau^I T^A Q)$

plus two "blind directions" from EW precision tests.

$$O_{HW} = (D^\mu\phi)^\dagger \tau_I (D^\nu\phi) W^I_{\mu\nu}, \quad O_{HB} = (D^\mu\phi)^\dagger (D^\nu\phi) B_{\mu\nu}.$$

[Grojean,Skiba,Terning,'06]

UV

- Comes from renormalization of the theory.
- What we do:
  - Dim-6: MSbar, for large logs and for we don't have ren conditions.
    - Running&mixing of coefficients: charatersized by 2499X2499 matrix.
    - First computed by [R. Alonso et al.] (and refs therein) but we always check.
  - Remaining finite effects modify the SM renormalization, wave functions and masses, g_s etc. e.g. from O_{tG}

R2

- R2 comes from the fact that MadLoop works in 4 dimension.
  - Loop amplitude: $\frac{1}{(2\pi)^4}\int d^d\bar{q}\frac{\bar{N}(\bar{q})}{\bar{D}_0\bar{D}_1\cdots\bar{D}_{m-1}}$, $\bar{D}_i = (\bar{q}+p_i)^2 - m_i^2$
  - MadLoop: numerical evaluates the 4-dimensional part, but need to add the missing D-4 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.

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

R2

- 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.