DETERMINATION OF THE TOP EW COUPLINGS VIA AN EFT APPROACH: THEORETICAL ASPECTS

Fabio Maltoni

Center for Cosmology, Particle Physics and Phenomenology (CP3),

UCLouvain Belgium

results obtained in collaboration with:

Olga Bylund, Celine Degrande, Gauthier Durieux, Ioannis Tsinikos, Eleni Vryonidou, Jian Wang, Cen Zhang...

THE EFT APPROACH

The matter content of SM has been experimentally verified and evidence for light states is not present.

SM measurements can always be seen as searches for deviations from the dim=4 SM Lagrangian predictions. More in general one can interpret measurements in terms of an EFT:

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

the BSM ambitions of the LHC Higgs/Top/SM physics programmes can be recast in a simple and powerful way in terms of one statement:

"BSM goal" of the SM LHC programme:

determination of the couplings of the SM $\mathcal{L}$ up to DIM=6

THE EFT APPROACH : SM@DIM6 LAGRANGIAN

[Grzadkowski et al, 10]

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_{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_{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_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

- Based on all the symmetries of the SM
- New physics is heavier than any other SM particle $\Lambda > M_X$
- QCD and EW renormalizable (order by order in $1/\Lambda$)
- Number of extra couplings reduced by symmetries and dimensional analysis
- Extends the reach of searches for NP beyond the collider energy.
- Valid only up to the scale Λ

THE EFT APPROACH

- Very powerful approach.
- Note, however, that it only makes sense if a **global constraining strategy** is used to extract information from the data:
  - assume all couplings might not be zero at the EW scale.
  - Identify the operators entering each observable.
  - find enough observables (cross sections, BR's, distributions,...) to constrain all operators.
  - solve the (linear) system.
  - Hierarchical approach on the couplings.

Anomalous Couplings vs EFT : WTB

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + \text{h.c.}$$

4-parameters

For recent work on Wtb determination:

TH:
Hioki, Ohkuma: 1511.03437
Auguilar-Saavedra, Bernabeu 1508.04592
Bernardo, Castro, et al. 1408.7063
Fabbrichesi, Pinamonti, Tonaro 1406.5393
Aguilar-Saavedra et al. 1105.0117

EXP:
ATLAS, 1510.03764
CMS, 1410.1154

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}F_+(1+\cos\theta^*)^2 + \frac{3}{4}F_0\sin^2\theta + \frac{3}{8}F_-(1-\cos\theta^*)^2 \qquad F_+ + F_0 + F_- = 1$$

- Note that several groups now take $V_{L/R}$, $g_{L/R}$ complex.
- when mb=0 the interference terms with the SM amplitude (i.e. the linear terms) in g_L and V_R vanish.
- the 4F-contact term not included in the analysis of decays because its interference with the SM is vanishingly small. The square, however is not necessary small.

AC vs EFT : Wtb example

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-}$$

$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + \text{h.c.}$$

4-parameters

$$\mathcal{L}_{\text{SM}}^{\text{dim}\,6} = \sum_k \frac{c_k}{\Lambda^2}\hat{O}_k$$

$$\begin{aligned}
\hat{O}_{\varphi q}^{(3)} &= (\varphi^{\dagger} i \overleftrightarrow{D}_{\mu}^{I}\varphi)(\bar{q}_L\sigma^I\gamma^{\mu}q_L) \\
\hat{O}_{\varphi tb} &= i(\tilde{\varphi}^{\dagger}D_{\mu}\varphi)(\bar{t}_R\gamma^{\mu}b_R) \\
\hat{O}_{tW} &= \bar{q}_L\sigma^{\mu\nu}\sigma^I t_R\tilde{\varphi}W_{\mu\nu}^I \\
\hat{O}_{bW} &= \bar{q}_L\sigma^{\mu\nu}\sigma^I b_R\varphi W_{\mu\nu}^I
\end{aligned}$$

4 coefficients

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\hat{O}_{bW} &= \bar{q}_L \sigma^{\mu\nu}\sigma^I b_R \varphi W^I_{\mu\nu}
\end{aligned}$$

4 coefficients

$$\begin{aligned}
V_L &= V_{tb} + c_{\varphi q}^{(3)}\frac{v^2}{\Lambda^2} \simeq 1 + c_{\varphi q}^{(3)}\frac{v^2}{\Lambda^2} \\
V_R &= \frac{1}{2}c_{\varphi tb}\frac{v^2}{\Lambda^2} \\
g_R &= \sqrt{2}\,c_{tW}\frac{v^2}{\Lambda^2} \\
g_L &= \sqrt{2}\,c_{bW}\frac{v^2}{\Lambda^2}\,.
\end{aligned}$$

ONE-TO-ONE MAPPING

AC VS EFT : WTB EXAMPLE

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-}$$
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g_L &= \sqrt{2}\,c_{bW}\frac{v^2}{\Lambda^2}\,.
\end{aligned}$$

ONE-TO-ONE MAPPING

So here, AC and EFT are equivalent?

NO!

AC vs EFT : WTB example

COMMENTS:

- The EFT approach is an expansion in $1/\Lambda^2$, so the contribution from the BSM couplings squared is (typically) higher order. Their impact needs to be evaluated separately.
- In the mb=0 limit only two operators contribute at $1/\Lambda^2$
- Parameters can be complex in both cases. However, the complexity of the EFT is constrained by the hermiticity of the operators => not all coefficients can be complex.
- The square of the BSM should be used for estimating uncertainties.
- The square of the BSM should be used to assess unitarity issues.

AC vs EFT : WTB example

MORE COMMENTS:

- Typically, other operators enter a physical observables, such as the ONE 4F operators (tblv or tbqq) in top decay and single-top production at LO. For combining with single-top production the 4F is necessary.

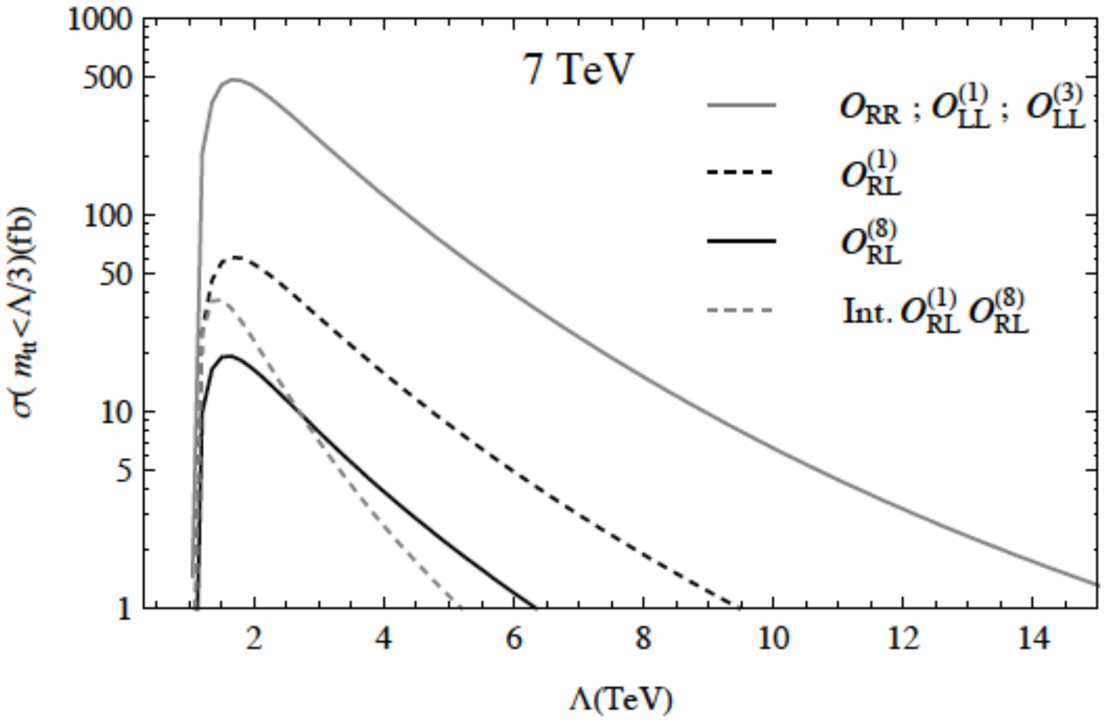
- Additional operators can contribute to a physical observable at higher-order in QCD. At NLO also Otg contributes to top decays.

- Operators do mix and can be assumed to be vanishing only at a given scale.

- EFT allows operators to be consistently constrained with other observables.

EFT validity

PP→TOP TOP



[Degrande et al. arXiv:1104.1798]

- Criteria to study the behaviour at HE include:
  - Series behaviour: $1/\Lambda^2$ vs $1/\Lambda^4$ (interference vs amplitude squared)
  - Unitarity
  - size of cross sections VS SM
  - validation/comparison with explicit UV completions
- Simple solutions (practical and legacy-friendly) are available:
  - simulations available for different values of $\Lambda>\sqrt{\hat{s}}$
- Possible improvements:
  - Event-by-event determination of the scale including running of the operators, i.e. QCD (and maybe EW) RGE effects *[Englert Spannowsky, arXiv:1104.1798].*

TOP-HIGGS INTERACTIONS

Consider, for example, the following top-Higgs interactions:

$$\mathcal{O}_{hg} = \left(\bar{Q}_L H\right) \sigma^{\mu\nu} T^a t_R G^a_{\mu\nu},$$ chromomagnetic operator

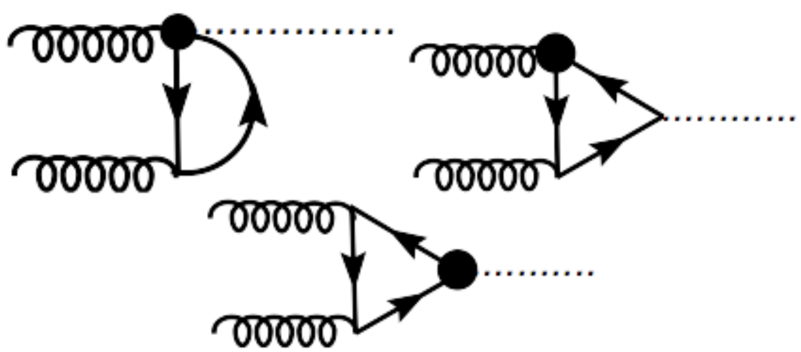
$$\mathcal{O}_{Hy} = H^\dagger H \left(H \bar{Q}_L\right) t_R$$ Yukawa operator

$$\mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$$ Higgs-gluon operator

At NLO in QCD the first two operators mix:

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

In addition, the third operator receives contributions from the first two at one loop:



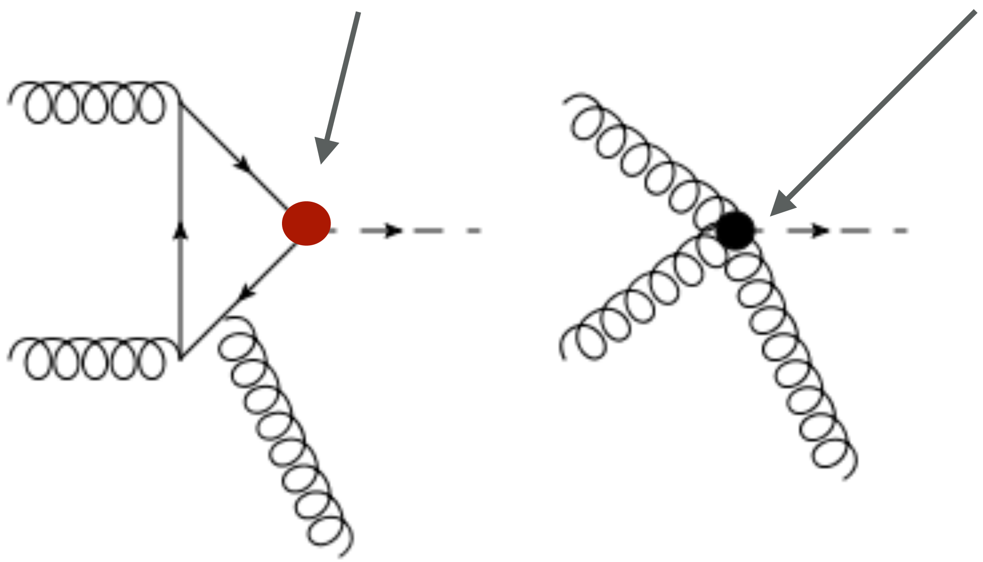
A meaningful analysis can only be made by considering them all!

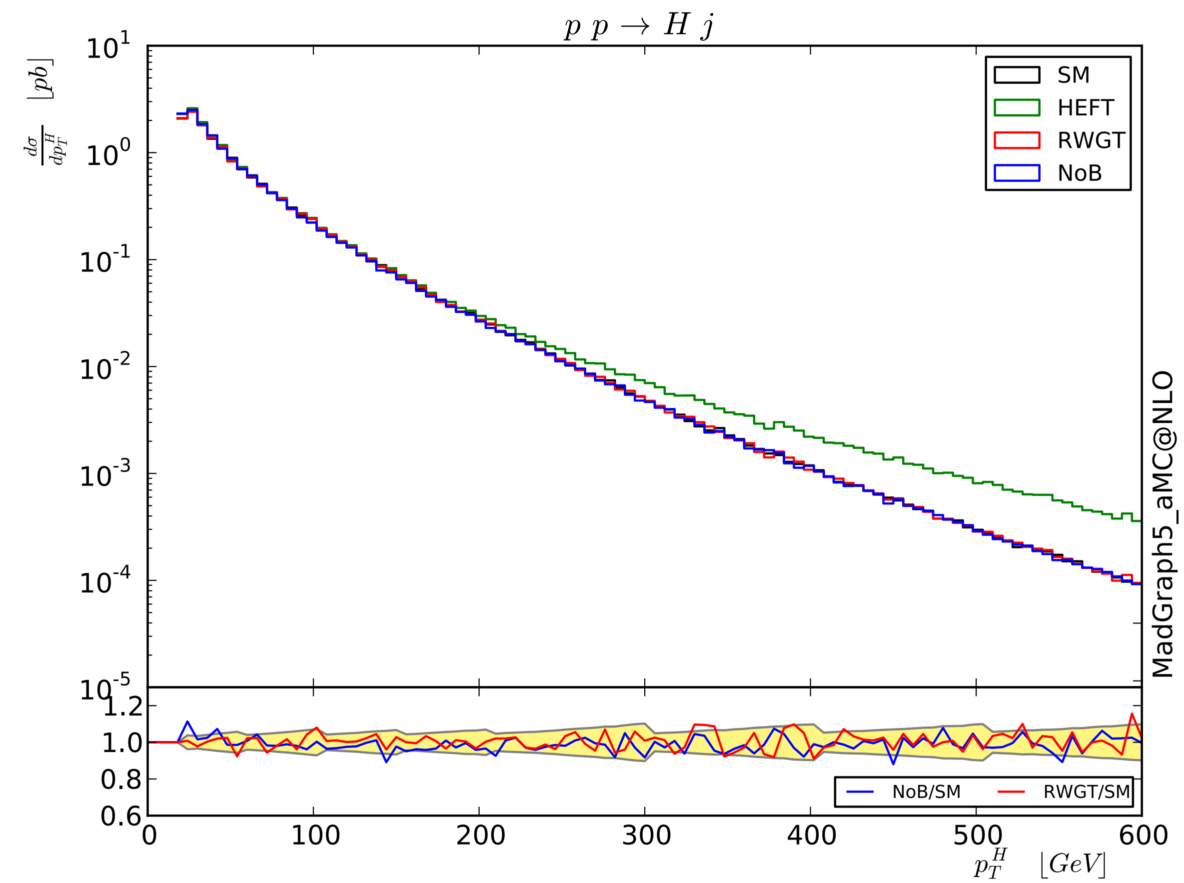
TOP-HIGGS INTERACTIONS: HIGH-PT

FROM A GLOBAL FIT THE COUPLING OF THE HIGGS TO THE TOP IS POORLY DETERMINED: THE LOOP COULD STILL BE DOMINATED BY NP.

[Grojean et al., 2013] [Banfi et al. 2014] [Buschmann, et al. 2014]

$$\mathcal{O}_{Hy} = H^\dagger H \left(H\bar{Q}_L\right) t_R \qquad \mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$$





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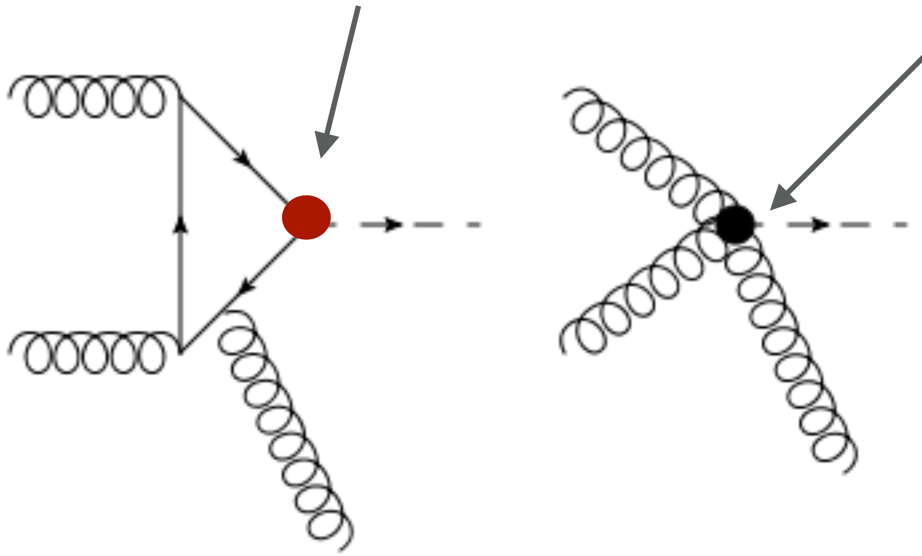
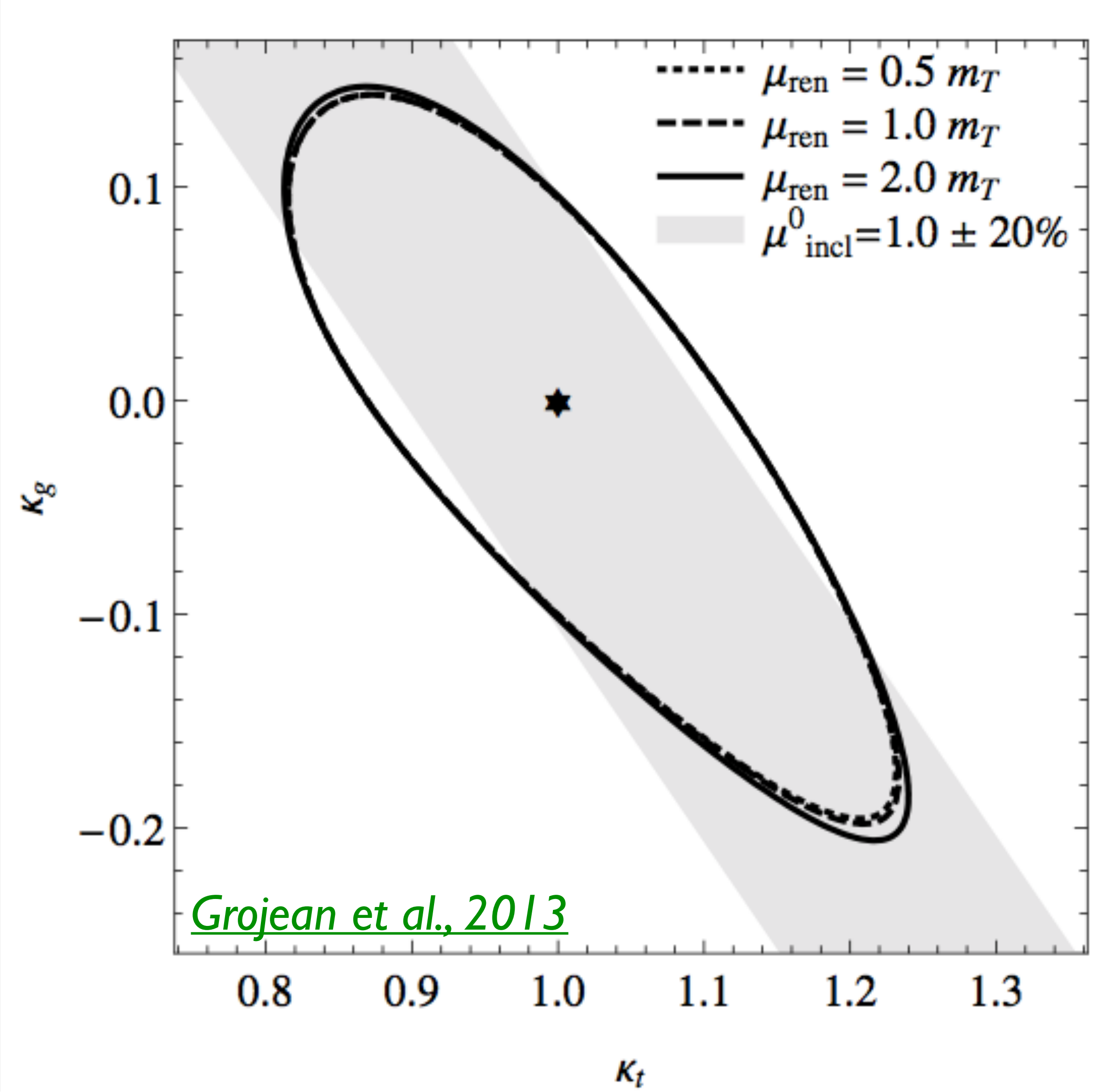
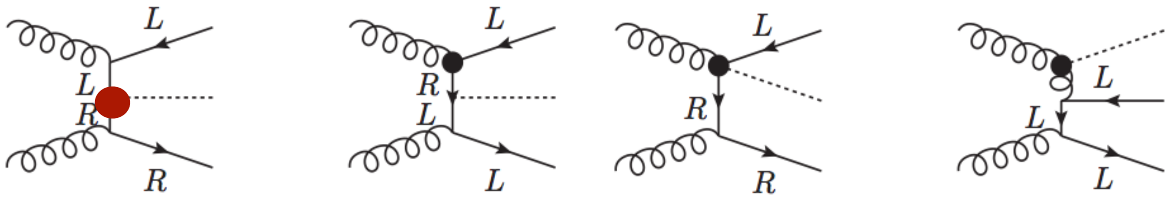


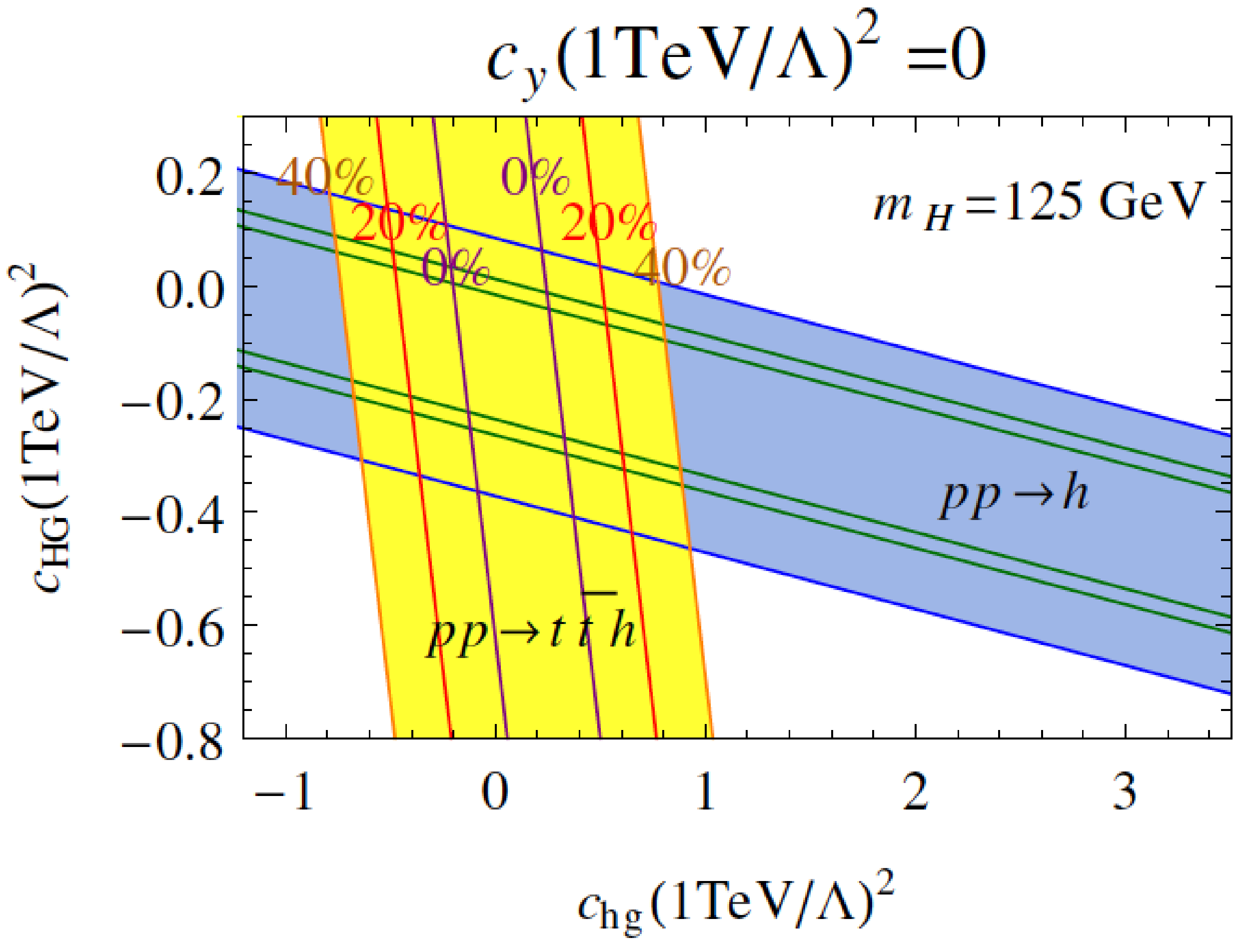


TOP-HIGGS INTERACTIONS: TTH

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

[Degrande et al. 2012]





$$
\begin{aligned}
\frac{\sigma\,(pp\to t\bar{t}h)}{\mathrm{fb}} = \; & 611^{+92}_{-110} + \left[457^{+127}_{-91}\Re c_{hg} - 49^{+15}_{-10} c_G \right.\\
& \left. + \; 147^{+55}_{-32} c_{HG} - 67^{+23}_{-16} c_y\right]\left(\frac{\mathrm{TeV}}{\Lambda}\right)^2 \\
& + \; \left[543^{+143}_{-123}(\Re c_{hg})^2 + 1132^{+323}_{-232} c_G^2 \right.\\
& + \; 85.5^{+73}_{-21} c_{HG}^2 + 2^{+0.7}_{-0.5} c_y^2 \\
& + \; 233^{+81}_{-144}\Re c_{hg} c_{HG} - 50^{+16}_{-14}\Re c_{hg} c_y \\
& \left. - \; 3.2^{+8}_{-8}\Re c_{Hy} c_{HG} - 1.2^{+8}_{-8} c_H c_{HG}\right]\left(\frac{\mathrm{TeV}}{\Lambda}\right)^4
\end{aligned}
$$

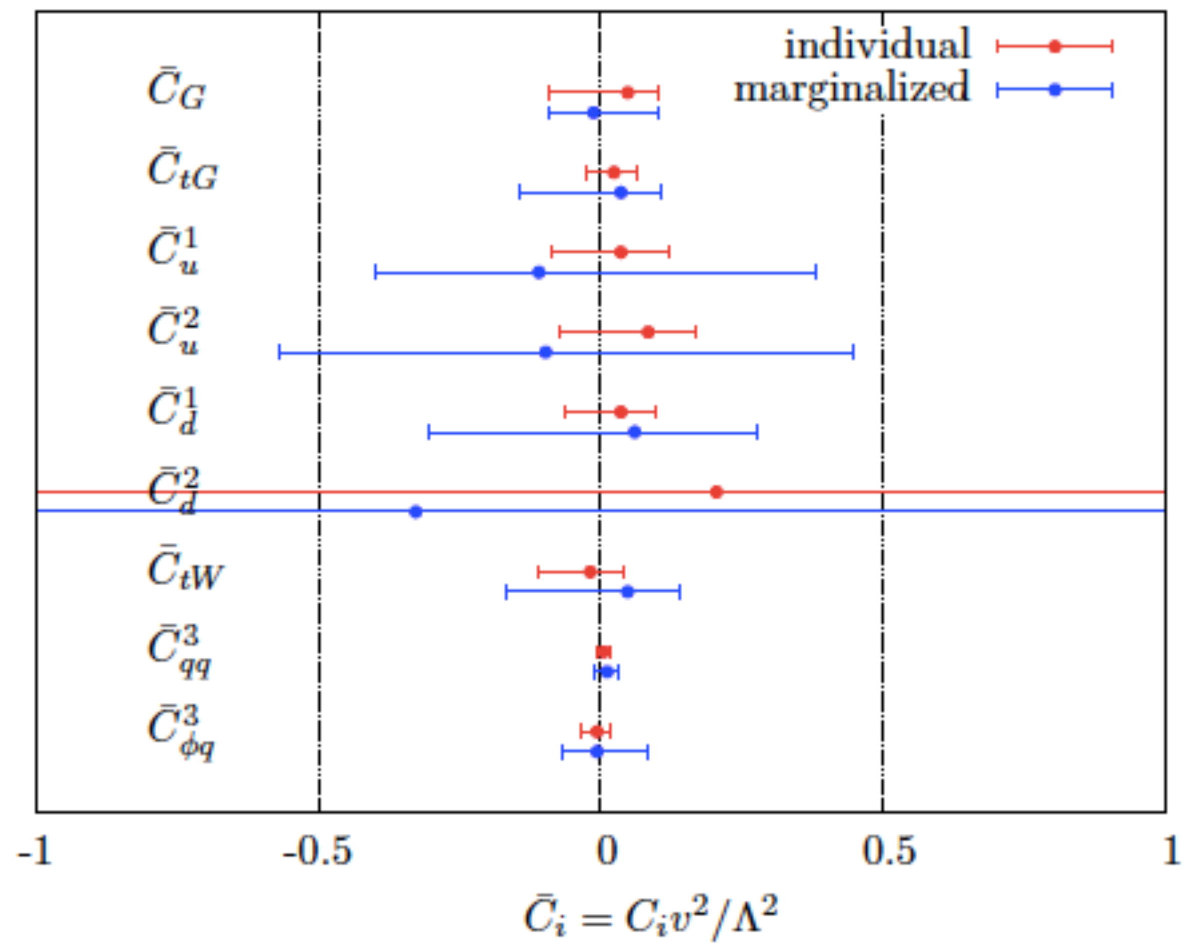
ANALYSIS DONE AT **LO! NLO** IS NOW WITHIN REACH

Towards a global fit at the LHC: A Proof of principle

[Buckley et al.,2015]

4-fermion operators		Non 4-fermion operators	
O^1_{qq}	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$	$O^3_{\phi q}$	$i(\phi^\dagger \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$
O^3_{qq}	$(\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)$	O_{tW}	$(\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W^I_{\mu\nu}$
O_{uu}	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$	O_{tG}	$(\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi}G^A_{\mu\nu}$
O^8_{qu}	$(\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)$	O_G	$f_{ABC}\, G^{A\nu}_\mu G^{B\lambda}_\nu G^{C\mu}_\lambda$
O^8_{qd}	$(\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)$	$O_{\tilde{G}}$	$f_{ABC}\, \tilde{G}^{A\nu}_\mu G^{B\lambda}_\nu G^{C\mu}_\lambda$
O^8_{ud}	$(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)$	$O_{\phi G}$	$(\phi^\dagger\phi)G^A_{\mu\nu}G^{A\mu\nu}$
		$O_{\phi\tilde{G}}$	$(\phi^\dagger\phi)\tilde{G}^A_{\mu\nu}G^{A\mu\nu}$

TABLE I: All dimension-six operators relevant to top quark production, in the notation of Ref. [12]. Details of each are included in the text. We do not include explicit flavor indices here. 13 operators are shown, but O_{tW} and O_{tG} have both real and imaginary parts which should be considered as independent operators; the latter produce $\mathcal{CP}$-violating effects.



- EFT based, fit on LHC data only: total as well as differential information from ttbar and t-channel single-top.
- SM at NLO or NNLO and EFT at LO in QCD (Feynrules+MadGraph).

Towards a global fit at the LHC

However, one has to pay attention to which operators contribute for a given process, LO and NLO.

[Cen Zhang]

Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	O_{G}	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	N		L	L				L		
$pp \to t\bar{q}$	N		L	L				L		
$pp \to tW$	L		L	L				N	N	N
$pp \to t\bar{t}$	L						N	L	L	L
$pp \to t\bar{t}\gamma$	L	L	L				N	L	L	L
$pp \to t\bar{t}Z$	L	L	L	L	L	L	N	L	L	L
$pp \to t\bar{t}h$	L						L	L	L	L
$gg \to H, H \to \gamma\gamma$	N						N			L

$O_G = g_s f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ and $O_{\varphi G} = g_s^2 \left(\varphi^\dagger \varphi\right) G_{\mu\nu}^A G^{A\mu\nu}$ are included because they mix with other top-quark operators and play a role in NLO calculations.

The need for NLO in QCD

- A global approach with constraints on top couplings coming from a wide set of observables is the (only) way to go.
- a precision physics effort needs accurate predictions not only for the SM but also for the EFT.
- This is because the top is coloured and the LHC is a hadron collider.
- In fact, the structure of the EFT for the top becomes non trivial at NLO in QCD, with operator mixings.

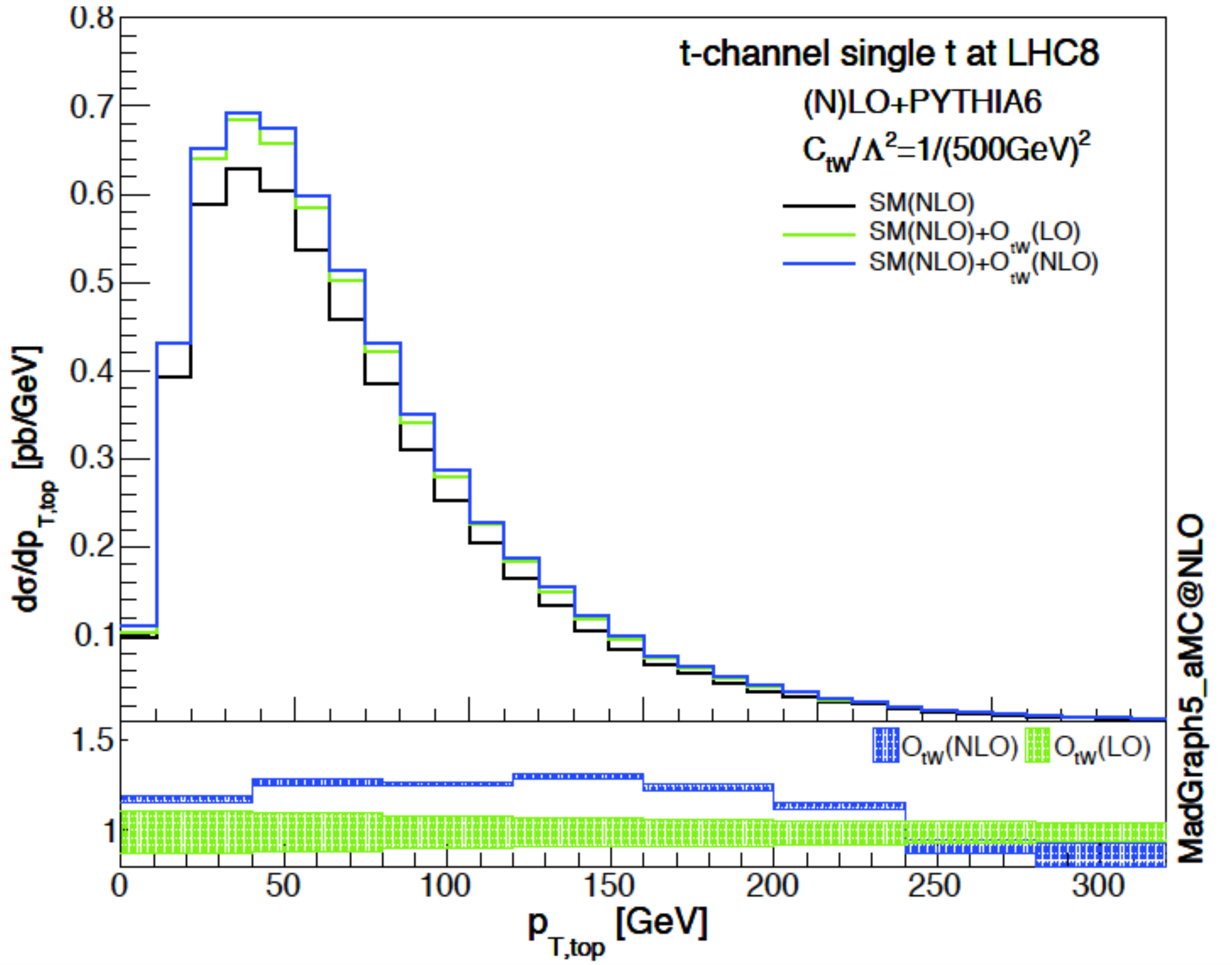
available MC tools

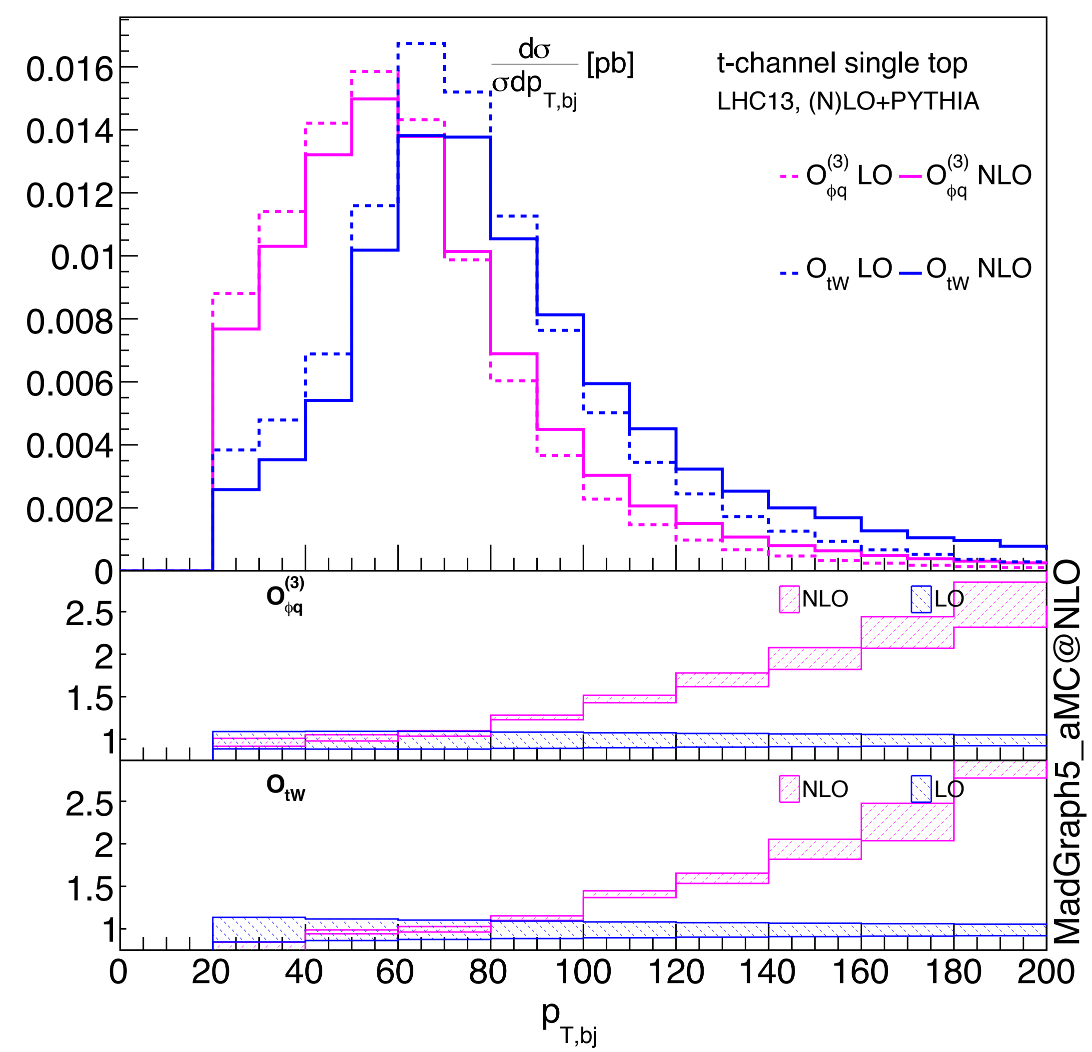
- Available Models (FeynRules/UFO)
  - full EFT dim=6 at LO
    - *https://feynrules.irmp.ucl.ac.be/wiki/HEL*
    - *https://feynrules.irmp.ucl.ac.be/wiki/BSMCharacterisation*
  - EFT involving top quarks dim=6 at LO
    - *https://feynrules.irmp.ucl.ac.be/wiki/TopEffTh*
  - EFT for FCNC at LO
    - *https://feynrules.irmp.ucl.ac.be/wiki/TFCNC*
    - *https://feynrules.irmp.ucl.ac.be/wiki/GeneralFCNTop*
  - EFT for FCNC at NLO
    - *(available on request)*
  - EFT involving top quarks dim=6 at NLO
    - *(available on request)*
- Dedicated tools and implementations at LO (eg PROTOS).
- Generic process* (via models above) : MadGraph5_aMC@NLO.

*Some limitations still apply.

T-CHANNEL IN THE EFT AT NLO

[Cen Zhang]





4F operator can also be included (on-going).

Bounding OtG at NLO from ttbar

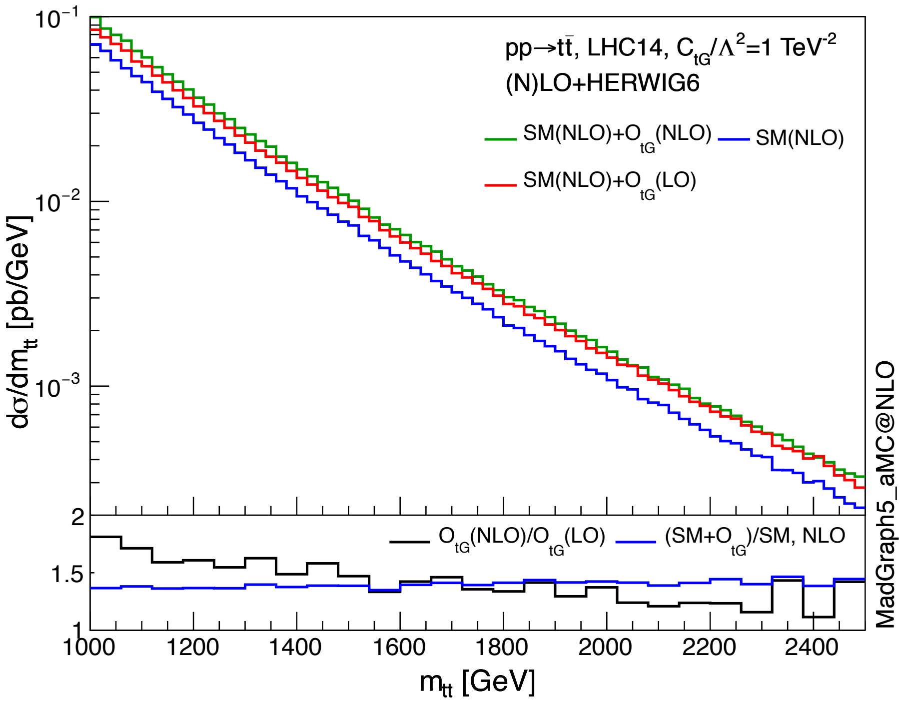
[Franzosi and Zhang, 2015]

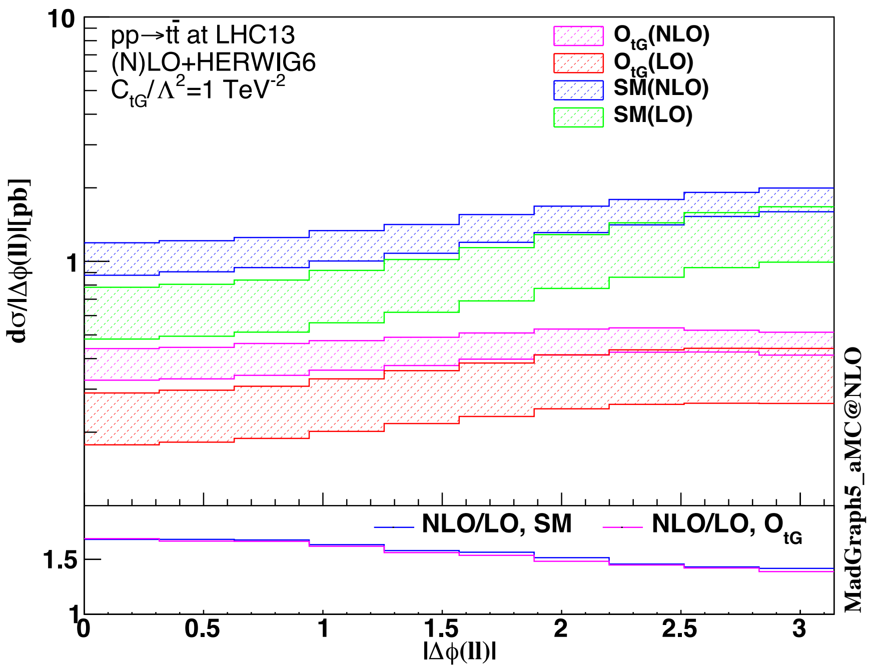
Recent analysis at NLO in QCD

$$\sigma = \sigma_{\rm SM} + \frac{C_{tG}}{\Lambda^2}\beta_1 + \left(\frac{C_{tG}}{\Lambda^2}\right)^2 \beta_2$$

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

β_2	LO [pb TeV^4]	NLO [pb TeV^4]
Tevatron	0.156	0.158
LHC8	8.94	11.8
LHC13	30.0	43.2
LHC14	35.7	51.6





Limits on ctG from LHC8

	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]

TTZ and TTγ : AC at NLO

[Rontsch and Shulze, 2014, 2015]

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

$$\mathcal{L}_{\gamma tt} = -eQ_t \bar{t}\,\gamma^\mu t\, A_\mu - e\bar{t}\,\frac{i\sigma^{\mu\nu} q_\nu}{m_t}(d_V^\gamma + i d_A^\gamma \gamma_5)\, t\, A_\mu$$

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

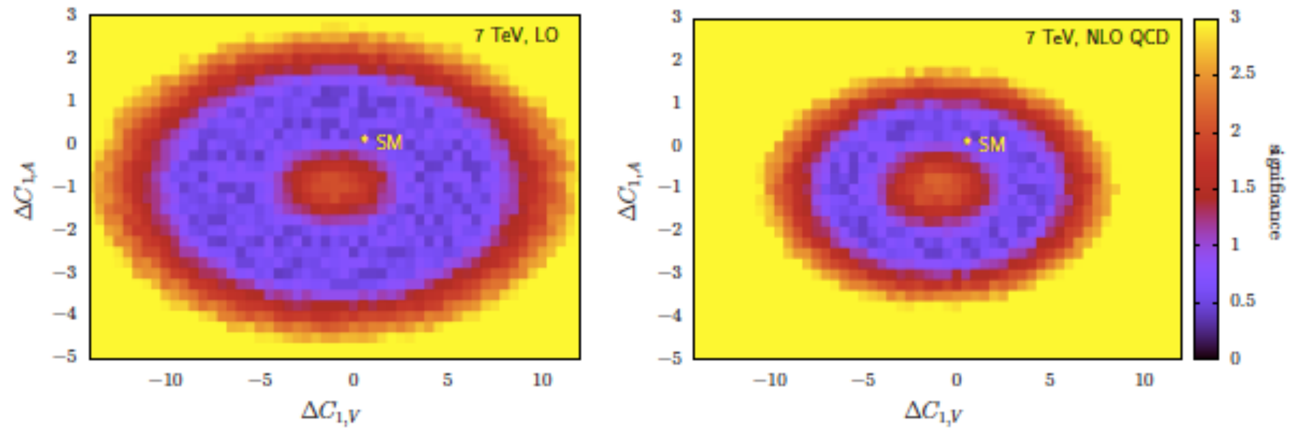
$$O_{\varphi Q}^{(1)} = i y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

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

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

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

- Top couplings not constrained by LEPI Z decays.
- the photon dipole coefficients depend on OtW and tB
- Photon and Z are related above the EWSB.
- Photon couplings enter in the off-shell tt$\ell\ell$

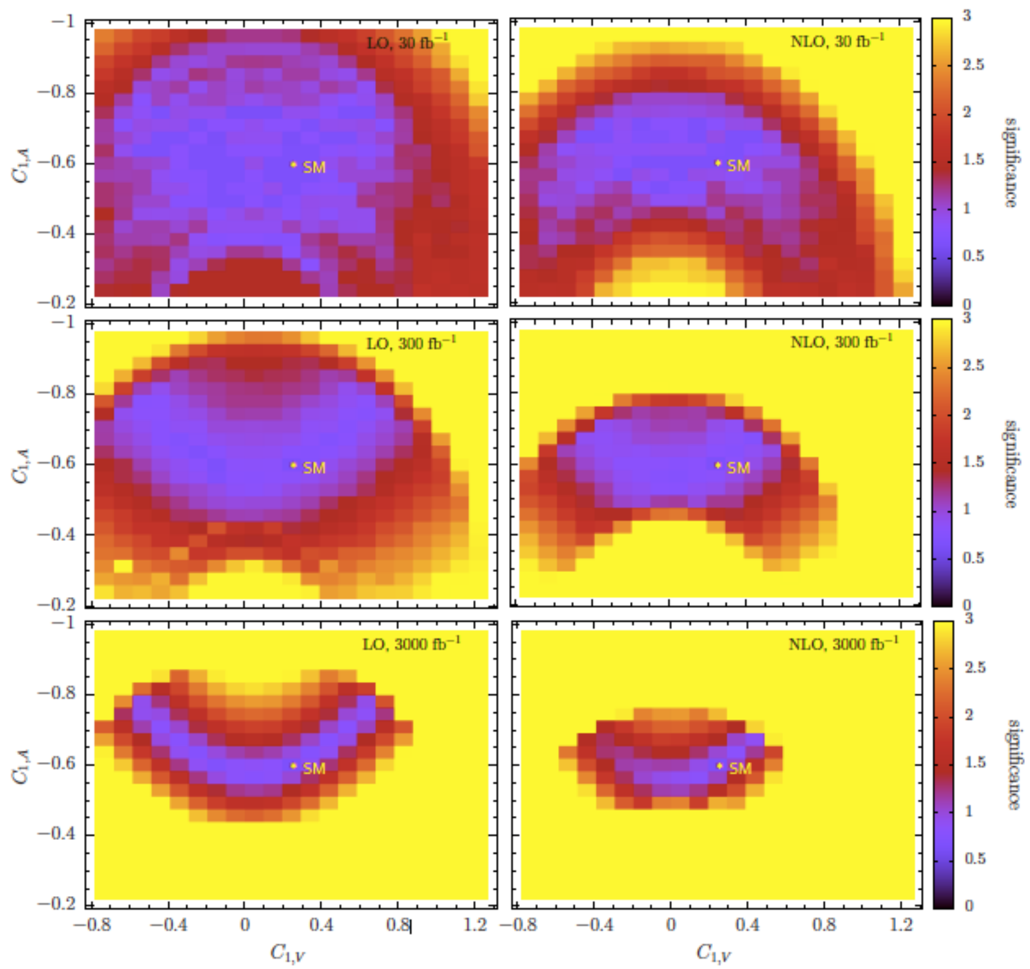


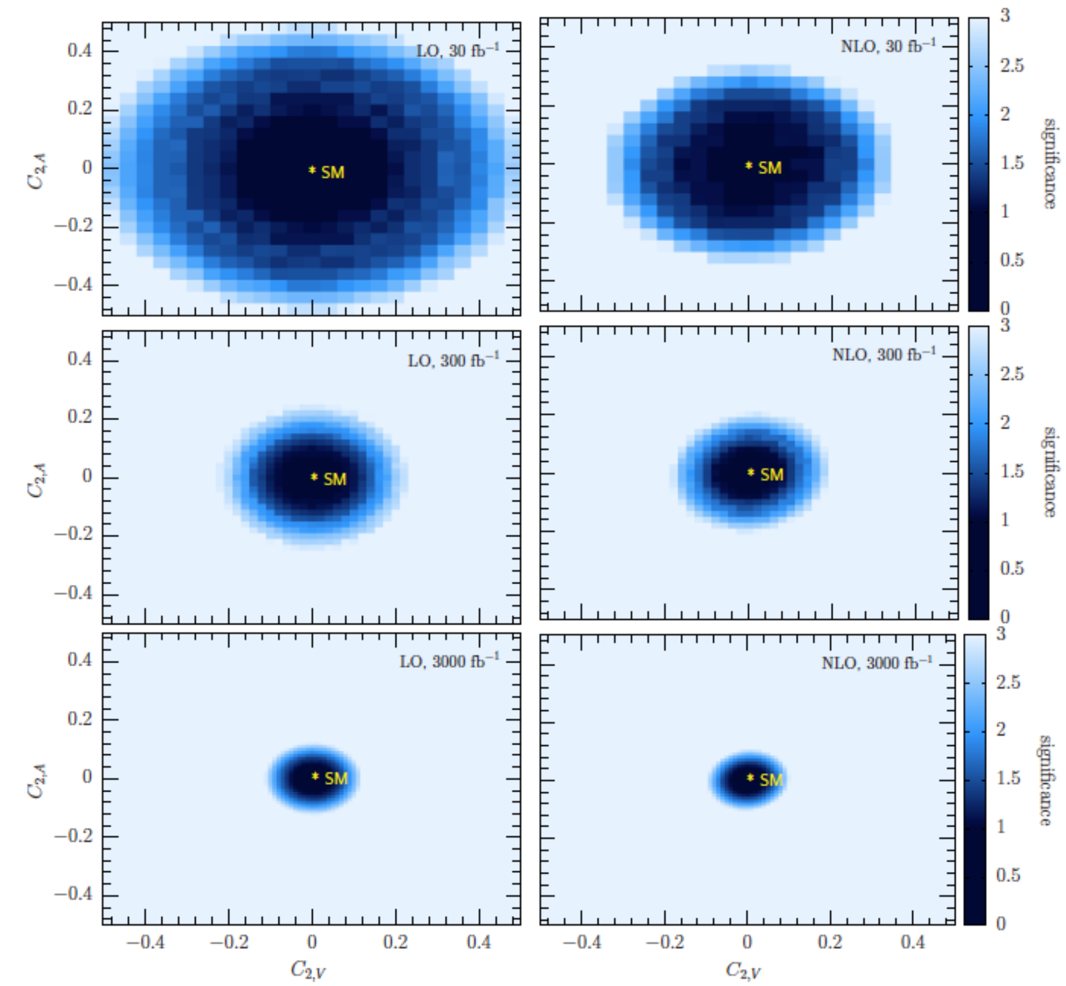
- Constraints from the 7 TeV Run

$$-8 \lesssim \Delta C_{1,V} \lesssim 7 \text{ and } -3 \lesssim \Delta C_{1,A} \lesssim 1$$

ttZ and ttγ : AC at NLO

[Rontsch and Shulze, 2014, 2015]





However more work needed:

- In essence still an anomalous coupling approach.
- Global analysis considering ttZ and ttγ needed.
- Constrains from LEP EW observables [Mebane et al, 2013]
- Also the chromomagnetic operator contributes to ttZ and ttγ. Given the present constraints it is quite important.
- four-fermion operators enter in the off-shell tt$\ell\ell$

Towards a global fit at NLO: ttV

[Bylund, FM, Tsinikos, Vryonidou, Zhang, in progress]

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$
$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$
$$O_{\varphi b} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{b}\gamma^\mu b)$$
$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$
$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$
$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}$$

O_{tg} is constrained from top pair production giving C_{tg}=[-0.77,0.4] [Aguilar-Saavedra:2014iga], LO [-0.56,0.41] and NLO [-0.42,0.30] [Franzosi:2015osa]. But as the contribution to the ttZ cross-section is big, we will not ignore this operator.

O_G is constrained from dijets. At the moment the only indication about limits is from [Ghosh:2014wxa], which claims a $|C_G| < 0.12$ based on some $t\bar{t}$ projection for the LHC with 30 fb^{-1} made in [Cho:1994yu]. We assume that dijet and $t\bar{t}$ cross-sections will constrain this, and we will not consider it any further.

O_{tW} is constrained from W helicity measurements and single top production, with limits C_{tW}=[-0.15,1.9] [Tonero:2014je].

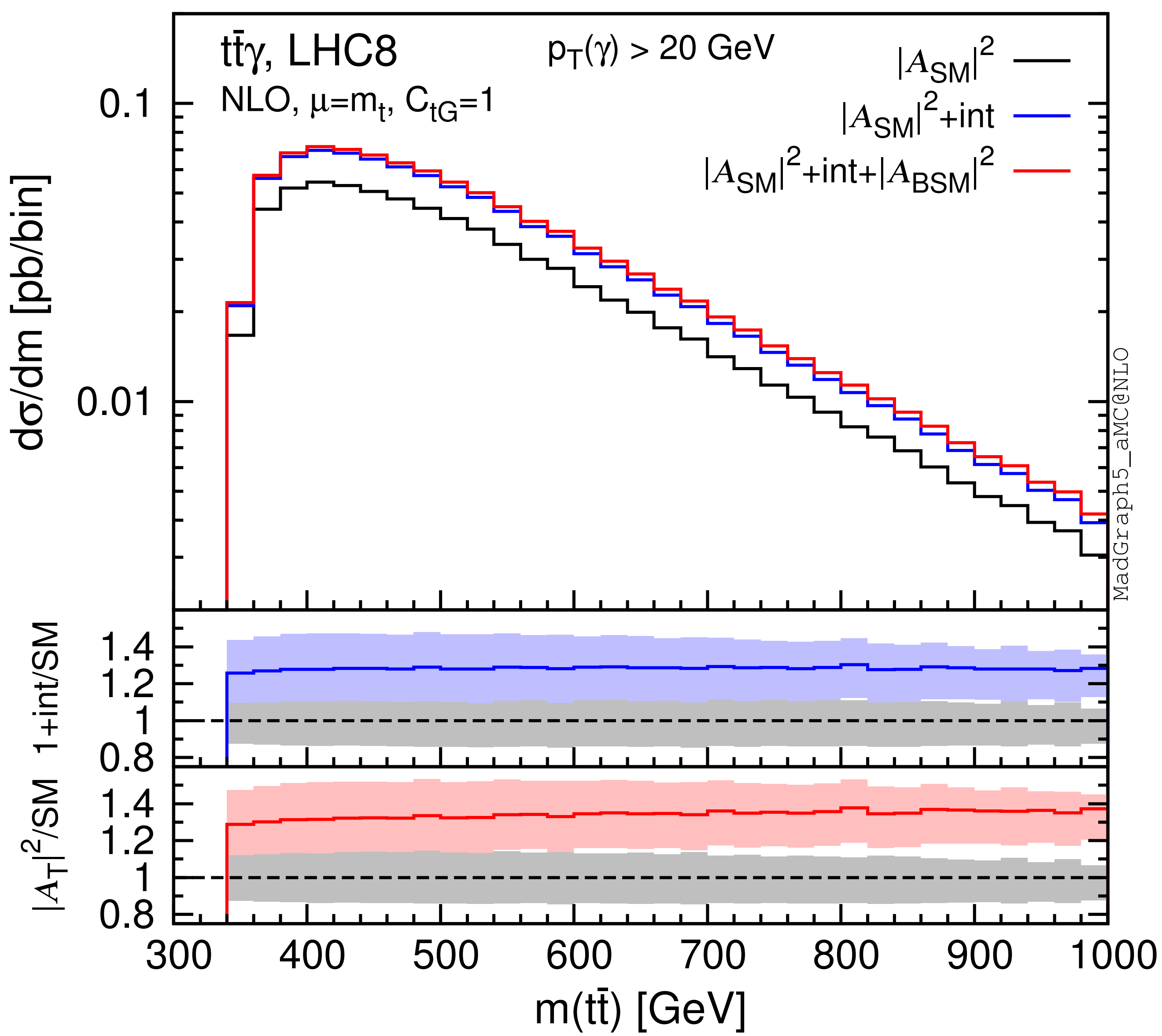
The $Z \to b\bar{b}$ decays contrains the sum of $C^{(3)}_{\phi Q} + C^{(1)}_{\phi Q}$=[-0.026, 0.059]. As this is already extremely constraining, in the rest of the study we will assume that $C^{(3)}_{\phi Q} + C^{(1)}_{\phi Q}$=0.

The other three: $O^{(3)}_{\phi Q} - O^{(1)}_{\phi Q}$, $O_{\phi t}$ and O_{tB} only receive indirect constraints from LEP giving the following limits:

$$C^{(3)}_{\phi Q} - C^{(1)}_{\phi Q} = [-3.4, 7.5]$$
$$C_{\phi t} = [-2.5, 7]$$
$$C_{tB} = [-17, 43]$$

TOWARDS A GLOBAL FIT AT NLO : TTγ

[Bylund, FM, Tsinikos, Vryonidou, Zhang, in progress]



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

$$C^\gamma_{2,V} = (C_{tW} + C_{tB})\frac{2m_t m_Z}{\Lambda^2}$$

$$C^\gamma_{2,A} = 0$$

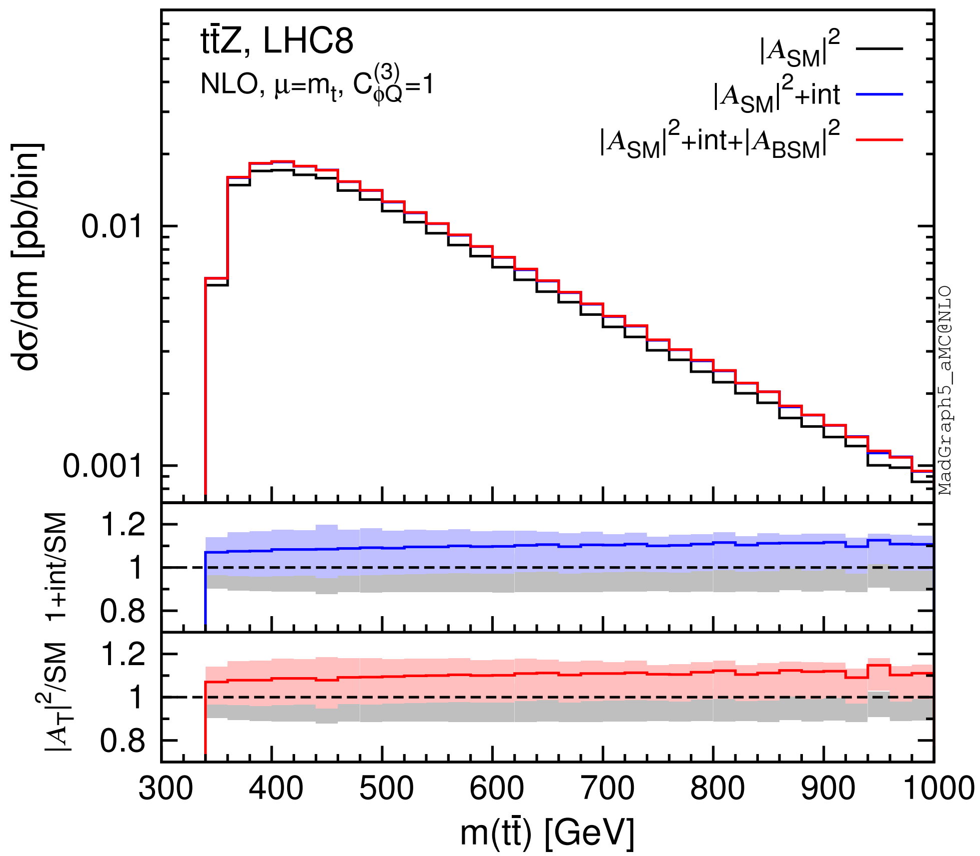
8TeV	SM	$\mathcal{O}_{tg}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$
$\sigma^{(1)}_{i,LO}$	$604.0(3)^{+234.1}_{-154.8}$	$171.5(1)^{+66.3}_{-43.9}$	$5.38(5)^{+2.26}_{-1.47}$	$5.38(5)^{+2.26}_{-1.47}$
$\sigma^{(1)}_{i,NLO}$	$777(1)^{+104}_{-107}$	$218.9(5)^{+29.1}_{-29.8}$	$5.8(1)^{+0.3}_{-0.5}$	$5.7(3)^{+0.3}_{-0.5}$
K-factor	1.29	1.28	1.08	1.06
$\sigma^{(1)}_{i,LO}/\sigma_{SM,LO}$		$0.2839(2)^{+0.0001}_{-0.0002}$	$0.0089(1)^{+0.0002}_{-0.0002}$	$0.0089(1)^{+0.0002}_{-0.0002}$
$\sigma^{(1)}_{i,NLO}/\sigma_{SM,NLO}$		$0.2817(8)^{+0.0004}_{-0.0005}$	$0.0074(2)^{+0.0004}_{-0.0007}$	$0.0073(4)^{+0.0004}_{-0.0007}$
$\sigma^{(2)}_{i,LO}/\sigma^{(1)}_{i,LO}$		$0.1740(2)^{+0.0061}_{-0.0052}$	$0.368(6)^{+0.015}_{-0.011}$	$0.368(6)^{+0.015}_{-0.011}$
$\sigma^{(2)}_{i,NLO}/\sigma^{(1)}_{i,NLO}$		$0.1789(8)^{+0.0010}_{-0.0017}$	$0.41(1)^{+0.02}_{-0.02}$	$0.42(3)^{+0.02}_{-0.02}$

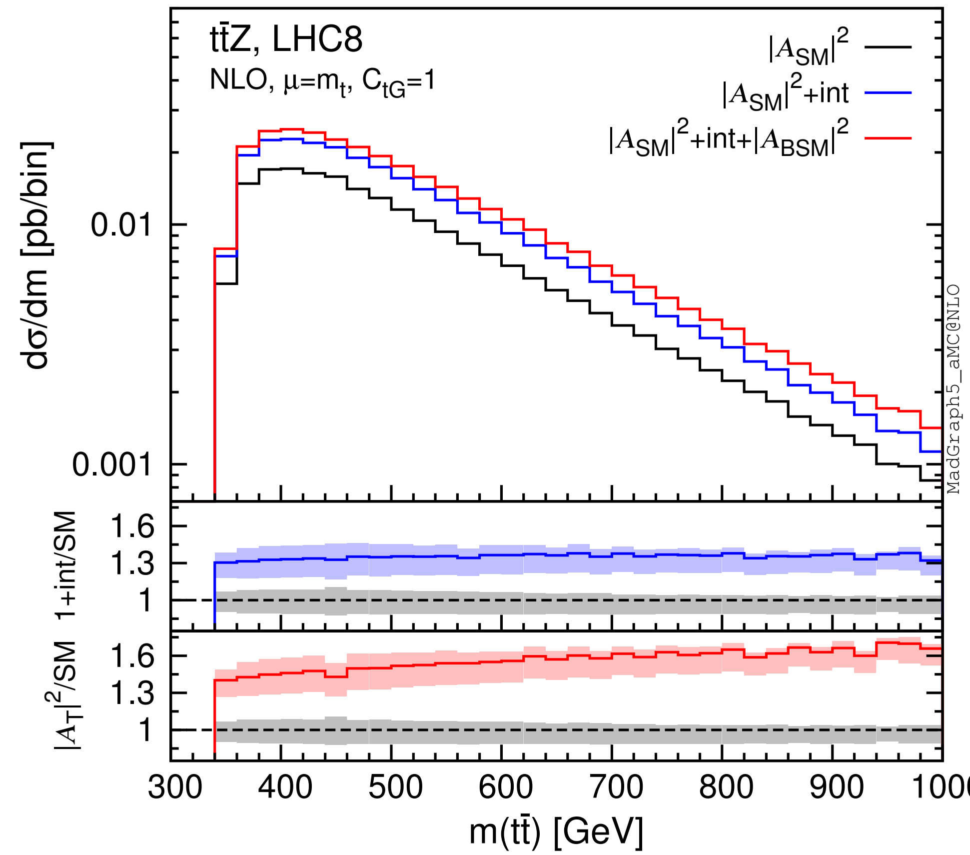
Table 3: Cross sections (in fb) for $t\bar{t}\gamma$ production at the LHC at $\sqrt{s} = 8$ TeV. No cuts are applied to final state particles except the $p_T(\gamma) > 20$ GeV cut, and no decays are included. The coefficient ctB at NLO in improved by using $c = \pm 50$.

CTW AND CTB ARE INDISTINGUISHIBLE. 1/Λ EXPANSION WELL BEHAVED.

TOWARDS A GLOBAL FIT AT NLO : TTZ

[Bylund, FM, Tsinikos, Vryonidou, Zhang, in progress]





8TeV	SM	$\mathcal{O}_{tg}$	$\mathcal{O}_{\phi Q}^{(1)}$	$\mathcal{O}_{\phi Q}^{(3)}$
$\sigma_{i,LO}^{(1)}$	$206.95(8)^{+85.65}_{-55.54}$	$76.10(7)^{+31.91}_{-20.62}$	$-18.49(3)^{+5.31}_{-8.40}$	$18.61(3)^{+8.41}_{-5.33}$
$\sigma_{i,NLO}^{(1)}$	$226.5(6)^{+15.2}_{-25.3}$	$78.1(2)^{+3.2}_{-7.8}$	$-20.81(7)^{+2.44}_{-1.25}$	$20.78(6)^{+1.16}_{-2.38}$
K-factor	1.09	1.03	1.13	1.12
$\sigma_{i,LO}^{(1)}/\sigma_{SM,LO}$		$0.3677(4)^{+0.0014}_{-0.0014}$	$-0.0893(2)^{+0.0023}_{-0.0026}$	$0.0899(1)^{+0.0025}_{-0.0022}$
$\sigma_{i,NLO}^{(1)}/\sigma_{SM,NLO}$		$0.345(1)^{+0.005}_{-0.0010}$	$-0.0919(4)^{+0.0006}_{-0.0006}$	$0.0918(4)^{+0.0006}_{-0.0010}$
$\sigma_{i,LO}^{(2)}/\sigma_{i,LO}^{(1)}$		$0.524(2)^{+0.043}_{-0.034}$	$-0.038(1)^{+0.0001}_{-0.0005}$	$0.039(1)^{+0.0001}_{-0.0002}$
$\sigma_{i,NLO}^{(2)}/\sigma_{i,NLO}^{(1)}$		$0.509(8)^{+0.007}_{-0.043}$	$-0.035(8)^{+0.003}_{-0.002}$	$0.037(8)^{+0.001}_{-0.002}$

8TeV	SM	$\mathcal{O}_{\phi t}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$
$\sigma_{i,LO}^{(1)}$	$206.95(8)^{+85.65}_{-55.54}$	$12.49(3)^{+5.57}_{-3.53}$	$-0.01(1)^{+0.01}_{-0.01}$	$0.08(2)^{+0.03}_{-0.03}$
$\sigma_{i,NLO}^{(1)}$	$226.5(6)^{+15.2}_{-25.3}$	$13.48(5)^{+0.66}_{-1.44}$	$0.11(4)^{+0.07}_{-0.04}$	$-0.32(2)^{+0.13}_{-0.22}$
K-factor	1.09	1.08	11	4
$\sigma_{i,LO}^{(1)}/\sigma_{SM,LO}$		$0.0604(1)^{+0.0014}_{-0.0012}$	$-0.0001(1)^{+0.00003}_{+0.00004}$	$0.0004(1)^{+0.0001}_{-0.0001}$
$\sigma_{i,NLO}^{(1)}/\sigma_{SM,NLO}$		$0.0595(3)^{+0.0005}_{-0.0014}$	$0.0005(2)^{+0.0003}_{-0.0001}$	$-0.0011(3)^{+0.0004}_{-0.0006}$
$\sigma_{i,LO}^{(2)}/\sigma_{i,LO}^{(1)}$		$0.058(2)^{+0.0007}_{-0.0004}$	$-30(30)^{+10}_{-30}$	$50(10)^{+20}_{-10}$
$\sigma_{i,NLO}^{(2)}/\sigma_{i,NLO}^{(1)}$		$0.06(1)^{+0.002}_{-0.003}$	$4(2)^{+2}_{-2}$	$-15(1)^{+6}_{-7}$

TOWARDS A GLOBAL FIT AT NLO: TTV

[Bylund, FM, Tsinikos, Vryonidou, Zhang, in progress]

preliminary

Coefficients	Fix	Fix (no ttV)	Marginalize	Marg. (no ttV)
$C_{\phi Q}^{(3)} + C_{\phi Q}^{(1)}$	[-0.025,0.056]	[-0.025,0.056]	[-0.025,0.058]	[-0.020,0.068]
$C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)}$	[-3.1,4.0]	[-3.4,7.5]	[-14,8]	[-40,12]
$C_{\phi t}$	[-2.4,4.5]	[-2.2,5.7]	[-11,17]	[-9.2,32]
C_{tW}	[-0.73,1.8]	[-0.74,1.8]	[-0.80,1.8]	[-0.67,2.0]
C_{tB}	[-13,44]	[-17,43]	[-43,67]	[-63,73]
C_{tG}	[-0.38,0.30]	[-0.40,0.31]	[-0.37,0.34]	[-0.40,0.31]

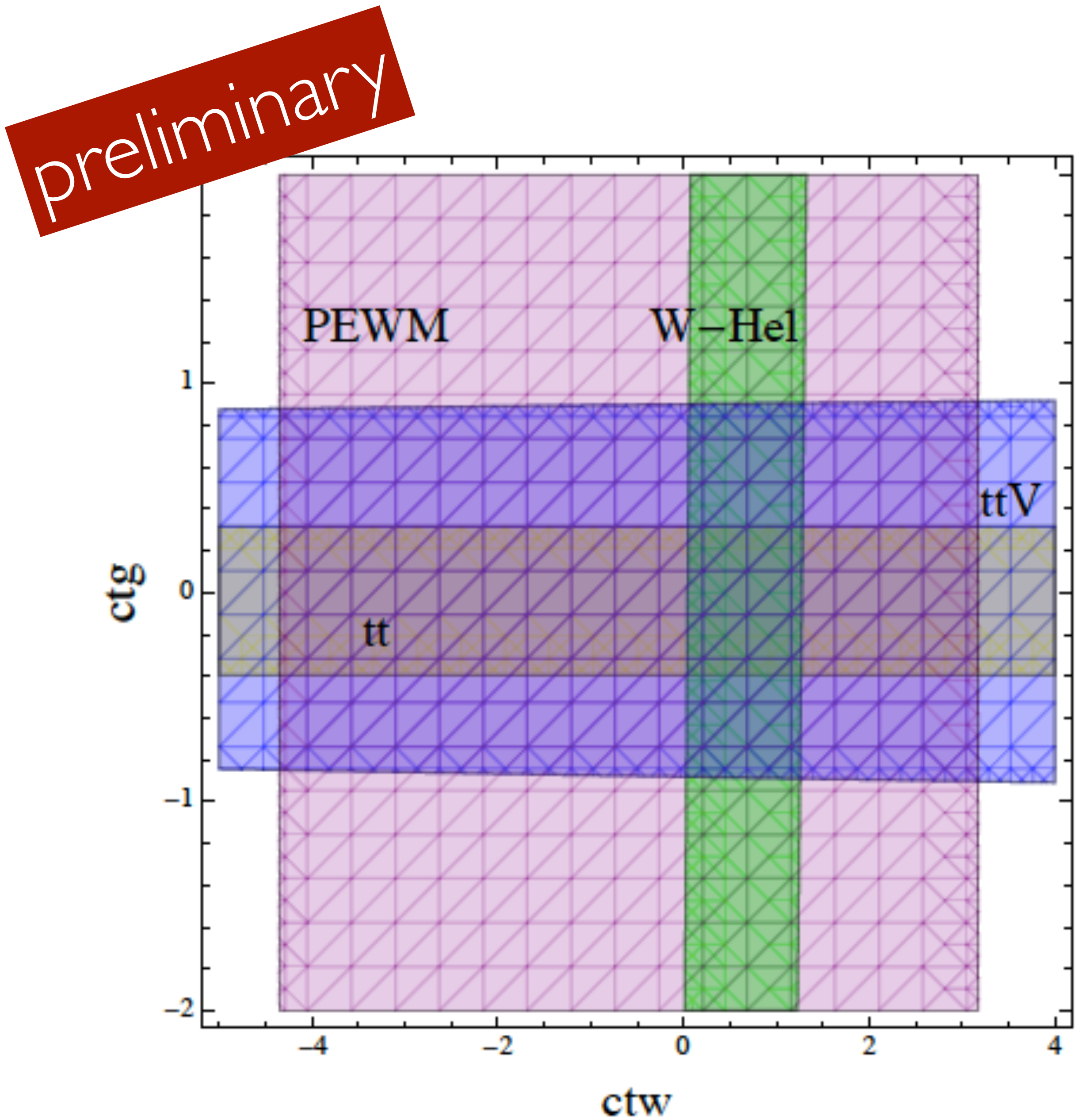
Table 8: Two-sigma bounds on individual operator, including $t\bar{t}V$+$t\bar{t}$+W-helicity+PEWM. $\Lambda \equiv 1$ TeV. Second column: all other coefficients are fixed to 0. Third column: same but without $t\bar{t}V$. Fourth column: all other coefficients are allowed to vary. Fifth column: same but without $t\bar{t}V$.

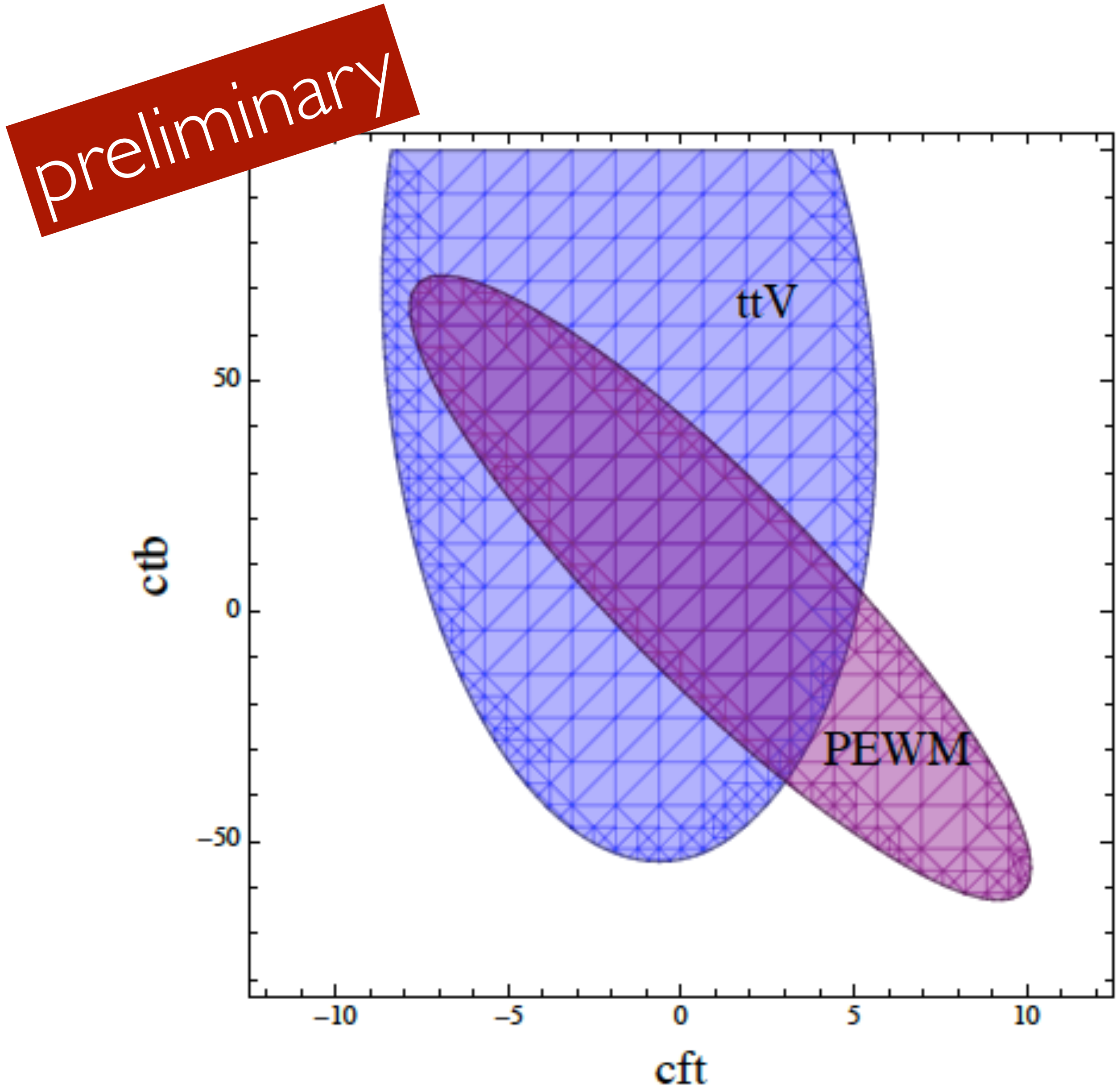
NO INFORMATION FROM SINGLE TOP PRODUCTION INCLUDED

IN THE PEWM FIT SOME ASSUMPTIONS ARE MADE.

TOWARDS A GLOBAL FIT AT NLO: TTV

[Bylund, FM, Tsinikos, Vryonidou, Zhang, in progress]





An EFT guy's desiderata

- Even if you are an adept of the AC approach and afraid to leave it, provide anyway the EFT interpretation of your bounds.
- If you use the EFT to interpret the results don't leave out operators without justification. clearly state which operators are included and why.
- Total cross sections are of limited use. More interesting are fiducial cross sections or pseudo-observables (eg helicity fractions). The best would be the direct fit (top-down) on the EFT coefficients using all possible kinematical information of the events (of course explore new observables).
- behaviour of the alphaS and 1/Λ expansions on observable basis should be always assessed for th uncertainties.
- Use at least NLO in QCD accuracy for the SM@DIM6

THE ROAD AHEAD

- The interpretation of most of the SM/Higgs/top measurements analyses can be recast in terms of the SM@DIM6 EFT.
- the precision of the theoretical predictions for the dim=4 SM will continue to be improved, by including NNLO in QCD and NLO in EW corrections in a fully exclusive way. Predictions for **EFT at NLO in QCD** are now **available** for a considerable set of operators.
- Proof of principle available of a global approach at NLO in QCD for FCNC top quark. Almost there for all top related operators (except 4F ops).
- Considerable work still to be done on how to define the best fitting strategy (and dealing with uncertainties).
  - NEW/EXCITING JOINT TH/EXP EFFORT!

Additional Material

TOWARDS A GLOBAL FIT AT NLO : TTZ

[Bylund, FM, Tsinikos, Vryonidou, Zhang, in progress]

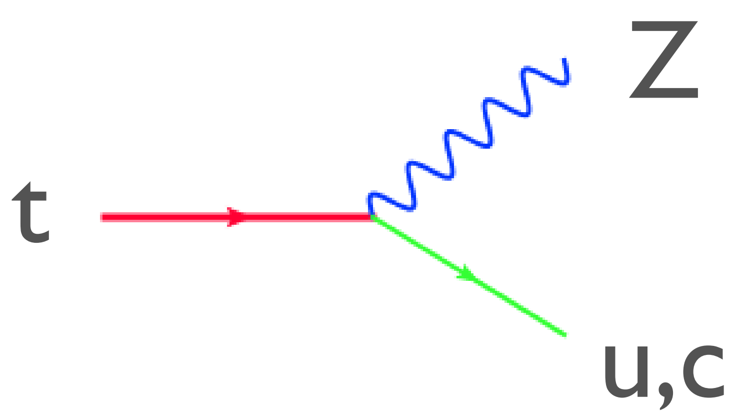
	Notation	Measurement	Reference
Z-pole	Γ_Z σ_{had} $R_f(f=e,\mu,\tau,b,c)$ $A_{FB}^{0,f}(f=e,\mu,\tau,b,c,s)$ $\bar{s}_l^2$ $A_f(f=e,\mu,\tau,b,c,s)$	Total Z width Hadronic cross section Ratios of decay rates Forward-backward asymmetries Hadronic charge asymmetry Polarized asymmetries	[25, 27]
Fermion pair production at LEP2	$\sigma_f(f=q,\mu,\tau,e)$ $A_{FB}^f(f=\mu,\tau)$	Total cross sections for $e^+e^-\to f\bar{f}$ Forward-backward asymmetries for $e^+e^-\to f\bar{f}$	[28]
W mass and decay rate	m_W Γ_W	W mass from LEP and Tevatron W width from Tevatron	[25]
DIS and atomic parity violation	$Q_W(Cs)$ $Q_W(Tl)$ $Q_W(e)$ g_L^2, g_R^2 $g_V^{\nu e}, g_A^{\nu e}$	Weak charge in Cs Weak charge in Tl Weak charge of the electron ν_μ-nucleon scattering from NuTeV ν-e scattering from CHARM II	[25]
W pair production	σ_W	Total cross section for $e^+e^-\to W^+W^-$	[28]

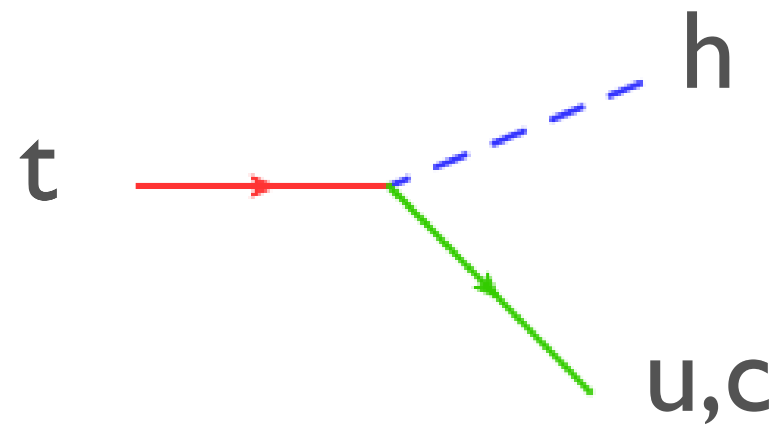
Table 1: Major precision electroweak measurements used in this analysis. The total cross section for $e^+e^-\to e^+e^-$ is divergent. We use the cross section in the angular range $\cos\theta\in[-0.9,0.9]$ instead.

Top FCNC at NLO

The study of FCNC couplings can bring new information:

[Drobnak, 2012 based on CMS and ATLAS results] [Kao et al. 2011 , Kai-Feng et al 2013] [Zhang FM, 2013]





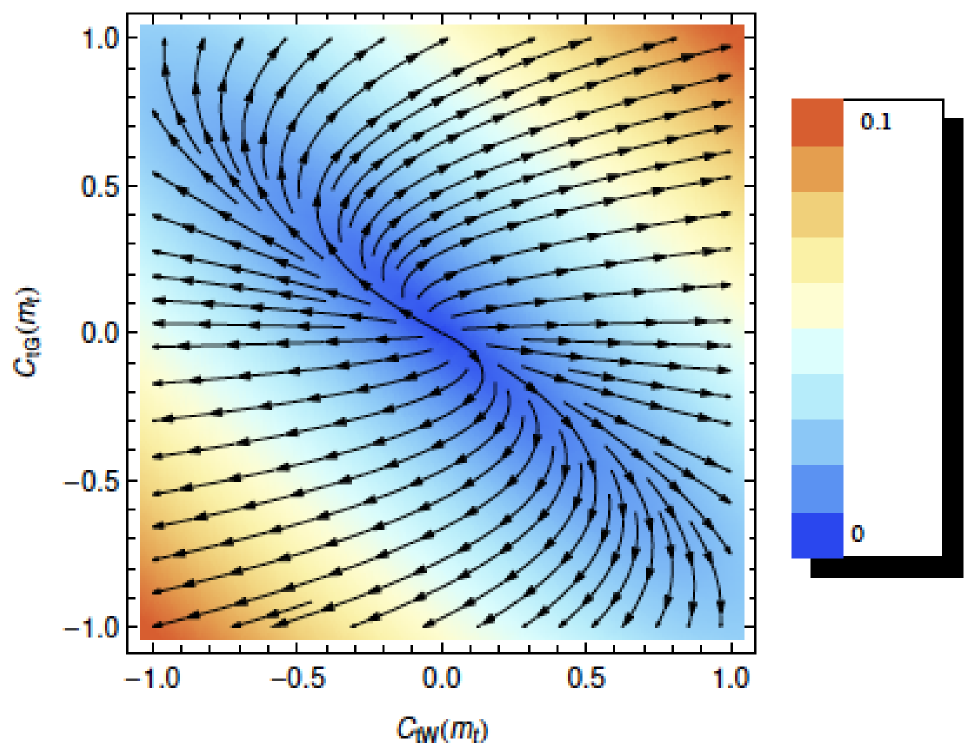
While the exp searches are completely different, one has to remember that the decay rates will depend on several operators that are linked by gauge symmetry. For example:

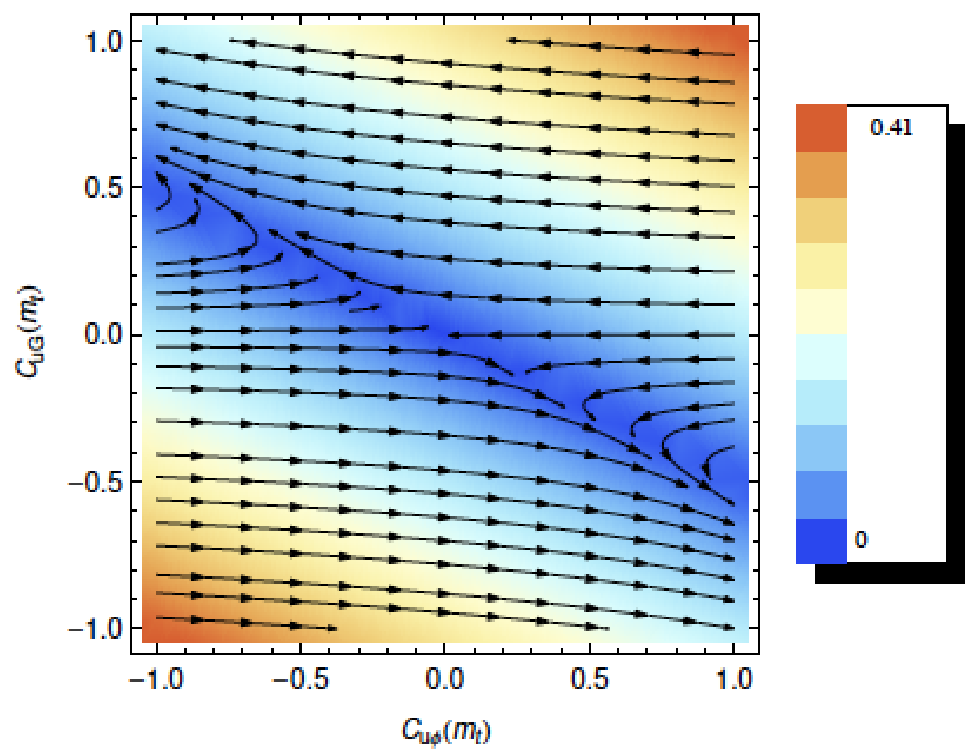
$$
\begin{aligned}
O_{uB}^{(13)} &= y_t g_Y (\bar{q}\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu} \\
O_{uW}^{(13)} &= y_t g_W (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu} \\
O_{uG}^{(13)} &= y_t g_s (\bar{q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu} \\
O_{u\varphi}^{(13)} &= -y_t^3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

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

Top FCNC at NLO

[Durieux, FM, Zhang 2014]





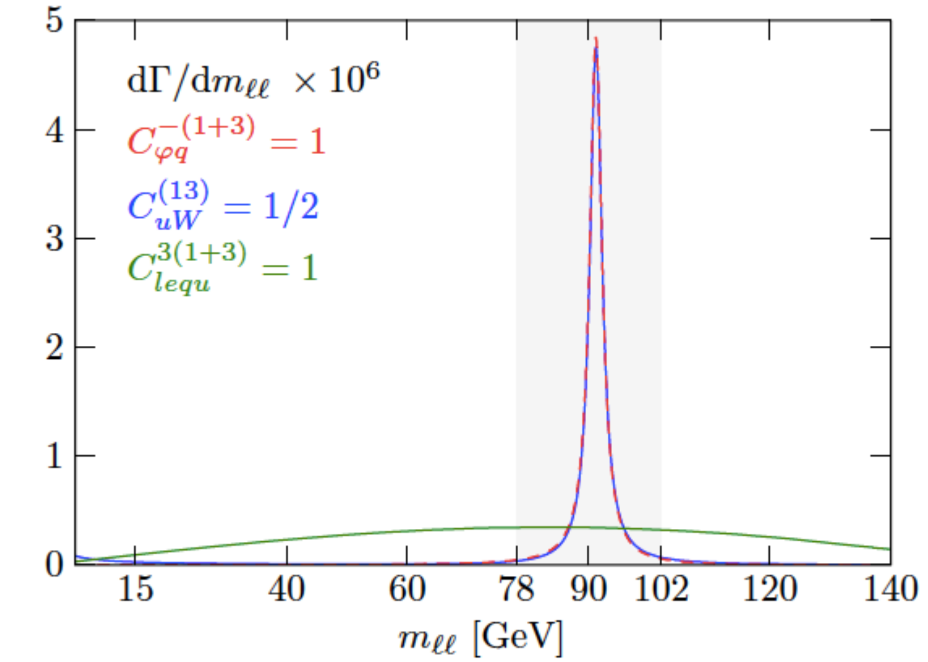
$$
\begin{aligned}
O_{tG} &= y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu} \\
O_{tW} &= y_t g_W (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu} \\
O_{tB} &= y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu} \\
O_{t\varphi} &= -y_t^3 (\varphi^\dagger\varphi)(\bar{Q}t)\tilde{\varphi}\ .
\end{aligned}
\qquad
\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} & 0 \\ -4 & 0 & 0 & -1 \end{pmatrix}
$$

$$
\begin{aligned}
O^{(13)}_{uG} &= y_t g_s (\bar{q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu} \\
O^{(13)}_{uW} &= y_t g_W (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu} \\
O^{(13)}_{uB} &= y_t g_Y (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu} \\
O^{(13)}_{u\varphi} &= -y_t^3 (\varphi^\dagger\varphi)(\bar{q}t)\tilde{\varphi}\ .
\end{aligned}
\qquad
\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} & 0 \\ -2 & 0 & 0 & -1 \end{pmatrix}
$$

$$
\begin{cases} C^{(13)}_{uG}(1\ \text{TeV}) = 1, \\ C^{(13)}_{u\varphi}(1\ \text{TeV}) = 0, \end{cases}
\longrightarrow
\begin{cases} C^{(13)}_{uG}(m_t) = 0.98, \\ C^{(13)}_{u\varphi}(m_t) = 0.23. \end{cases}
$$

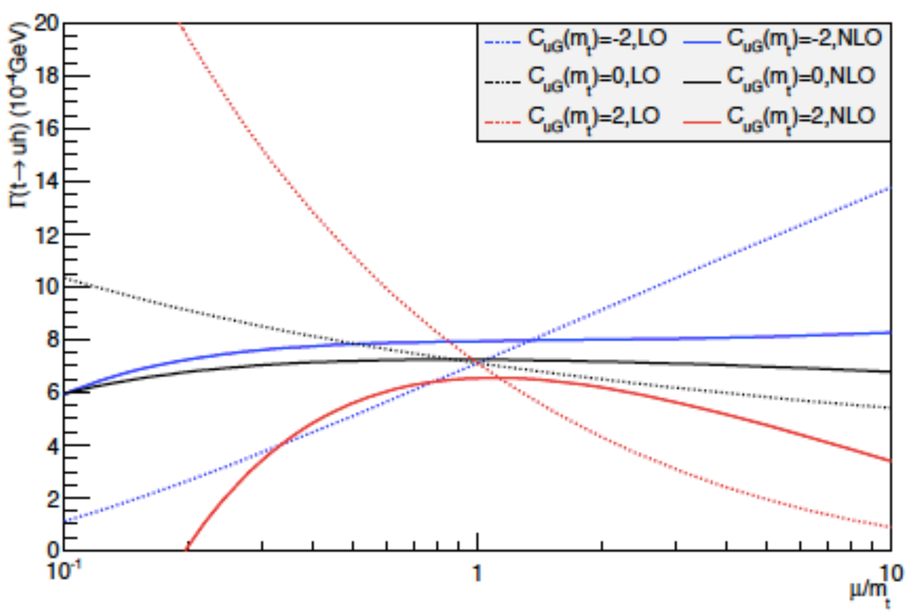
Top FCNC at NLO : decays

[Durieux, FM, Zhang 2014]



$$\Gamma^{\text{on-peak}}_{t\to u\, e^+e^-}\ /10^{-5}\ \text{GeV}\ \times (\Lambda/1\,\text{TeV})^4$$
$$= 1.7\,|C_{\varphi q}^{-(1+3)}|^2 + 6.6\,|C_{uW}^{(13)}|^2 + 0.81\,|C_{lequ}^{3(13)}|^2$$

$$\Gamma^{\text{off-peak}}_{t\to u\, e^+e^-}\ /10^{-5}\ \text{GeV}\ \times (\Lambda/1\,\text{TeV})^4$$
$$= 0.2\,|C_{\varphi q}^{-(1+3)}|^2 + 1.0\,|C_{uW}^{(13)}|^2 + 2.7\,|C_{lequ}^{3(13)}|^2$$



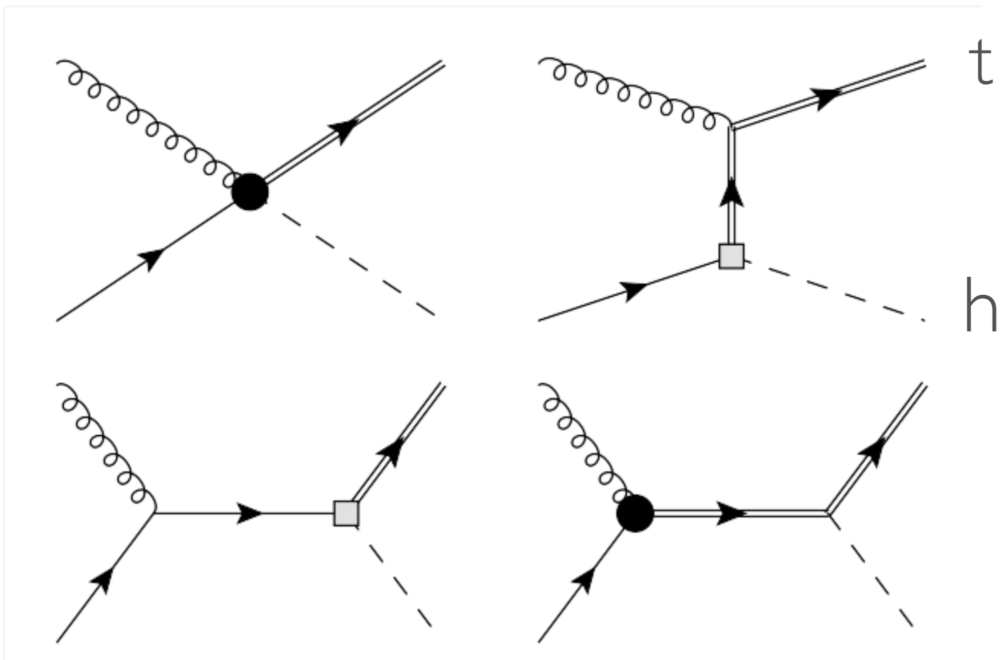
$$\Gamma(t\to u_i h) = \Gamma^{(0)} + \alpha_s \Gamma^{(1)}$$

$$\Gamma^{(0)} = 7.11|C_{u\varphi}(\mu)|^2\ \times 10^{-4}\,\text{GeV}\,,$$
$$\Gamma^{(1)} = \left\{ \left[1.19 - 9.05\log\left(\frac{m_t}{\mu}\right)\right]|C_{u\varphi}(\mu)|^2 - \left[3.26 + 18.1\log\left(\frac{m_t}{\mu}\right)\right]\mathrm{Re}C_{uG}(\mu)C^*_{u\varphi} + 9.33\times 10^{-5}|C_{uG}(\mu)|^2 \right\} \times 10^{-4}\,\text{GeV}\,. \quad (48)$$

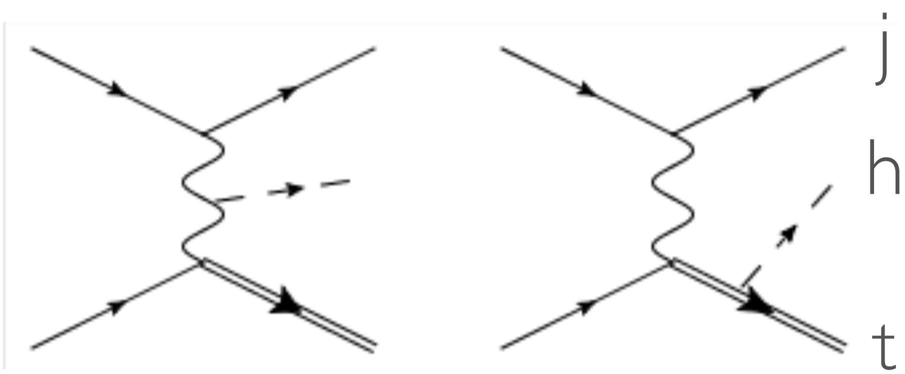
Top FCNC at NLO : production

[Degrande, FM, Wang, Zhang, 2014]

$pp \to th$



$pp \to thj$ (SM)



Contributions appear at LO from $O_{t\phi}$ and one from O_{tG}..

At NLO in QCD O_{tG} mixes with all the other operators so it has always to be included.

It also means that if a specific (arbitrary) choice of non-zero coefficient operators is made at high scales (where one can imagine a full theory to live) many operators become active when evolved to lower scales.

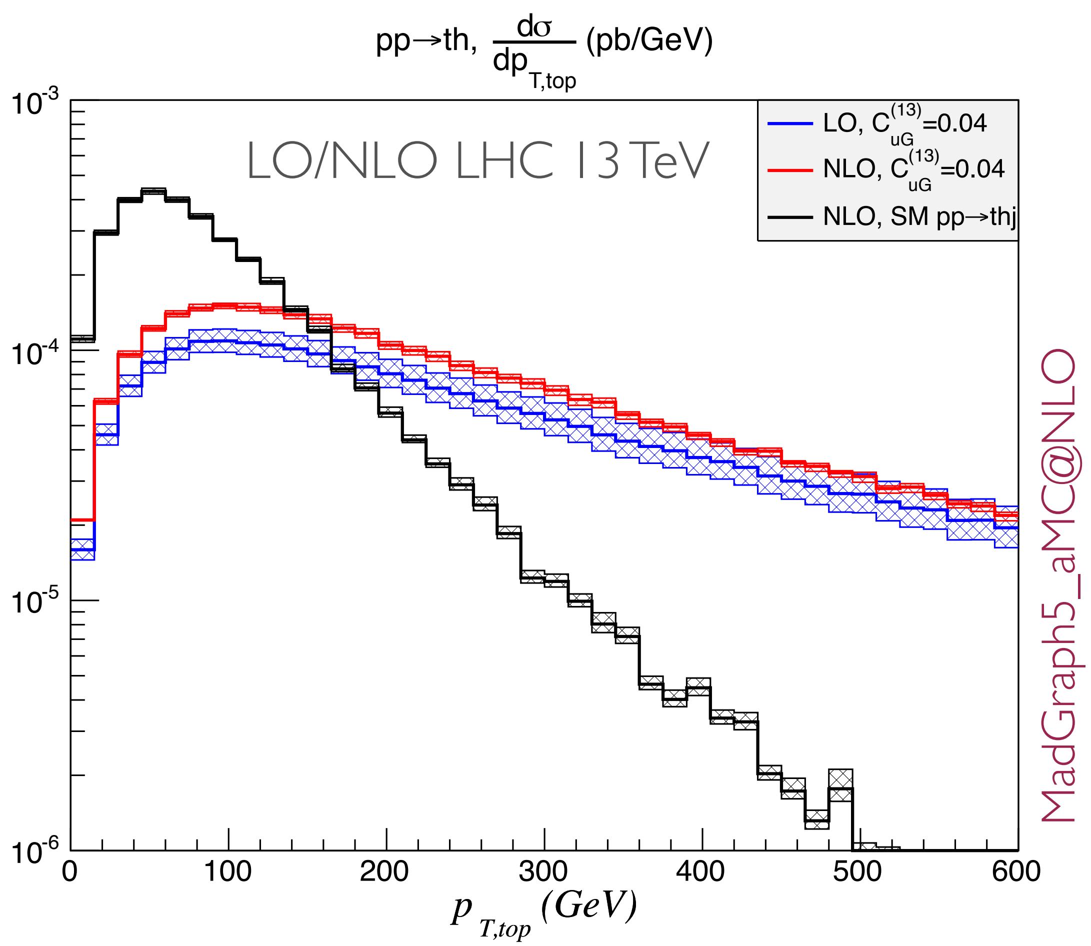
Only a global/fit approach on constraining such operators at the same time can be useful strategy and it has to be at least NLO in QCD.

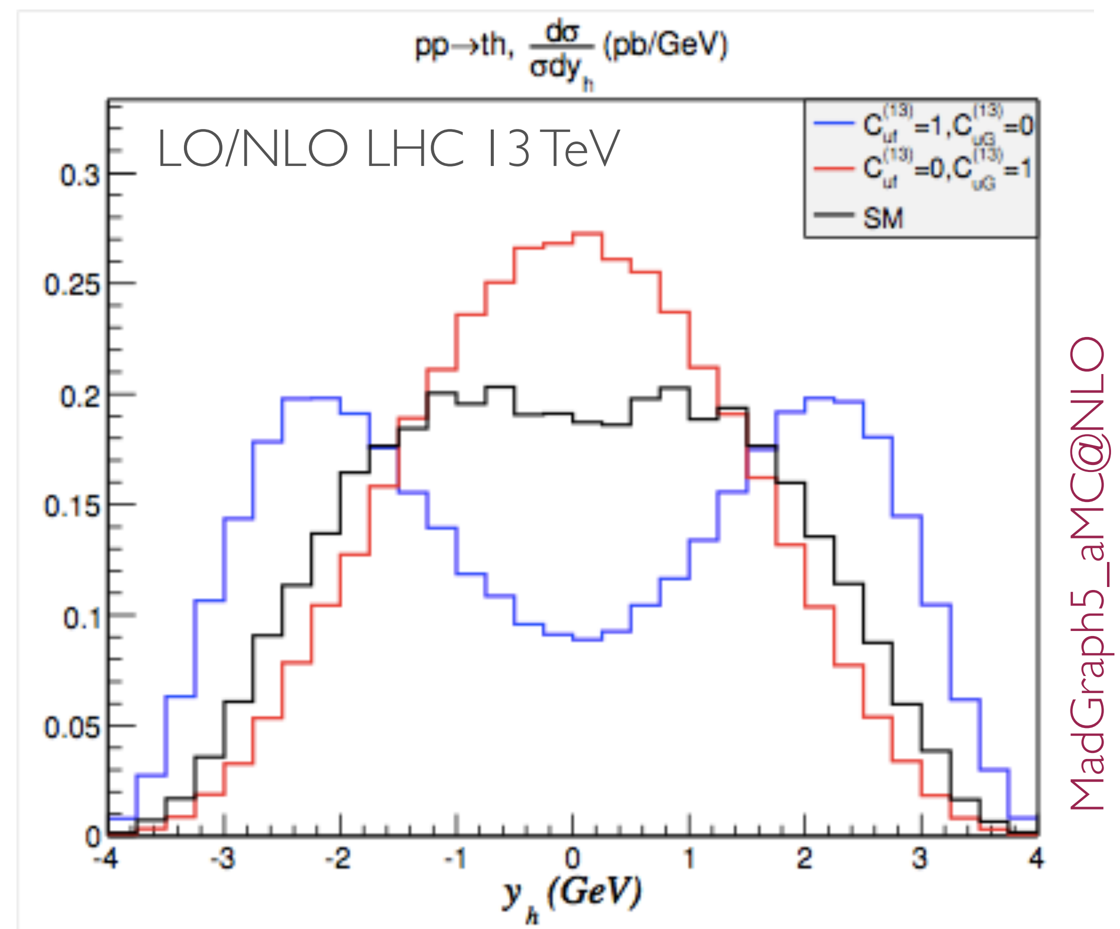
Top FCNC at NLO : production

[Degrande, FM, Wang, Zhang, 2014]

The operators have been implemented in FeynRules, the model was upgraded to NLO automatically and then passed to MG5_aMC.

Results shown here at NLO. the pp →thj interesting process by itself...





Complete implementation of all operators of dim=6 at NLO (including four fermion operators) in QCD is on going.

Top FCNC at NLO : global fit

[Durieux, FM, Zhang 2014]

$$\mathrm{Br}(t \to j\, e^+e^-) + \mathrm{Br}(t \to j\, \mu^+\mu^-) \lesssim 0.0017\%$$ CMS

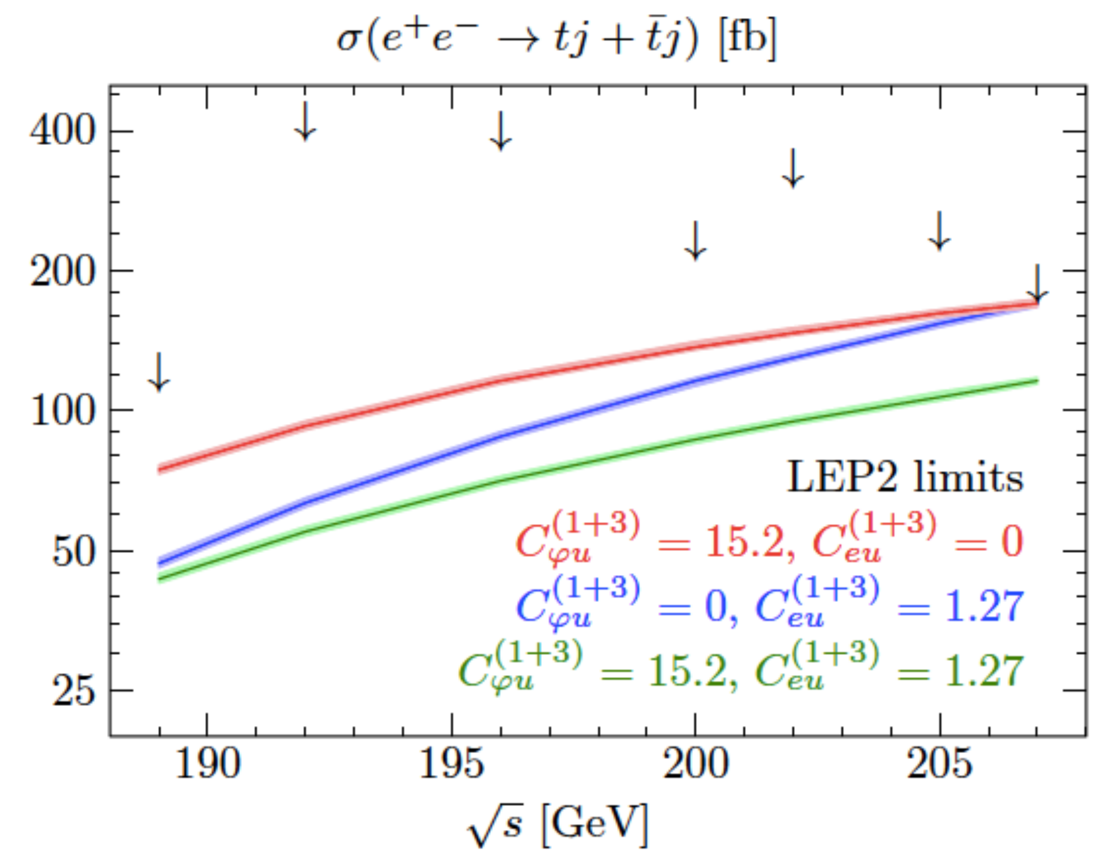
$$\mathrm{Br}(t \to j\gamma) < 3.2\%$$ CDF

$$\mathrm{Br}(t \to j\,\gamma\gamma) < 0.0016\%$$ CMS

$$\sigma(pp \to t) + \sigma(pp \to \bar{t}) < 2.5 \text{ pb} \quad \text{at } \sqrt{s} = 8 \text{ TeV}$$ ATLAS

$$\sigma(ug \to t\gamma) + \sigma(ug \to \bar{t}\gamma) + 0.778\,\left[\sigma(cg \to t\gamma) + \sigma(cg \to \bar{t}\gamma)\right] < 0.0670 \text{ pb} \quad \text{at } \sqrt{s_{pp}} = 8 \text{ TeV}$$ CMS

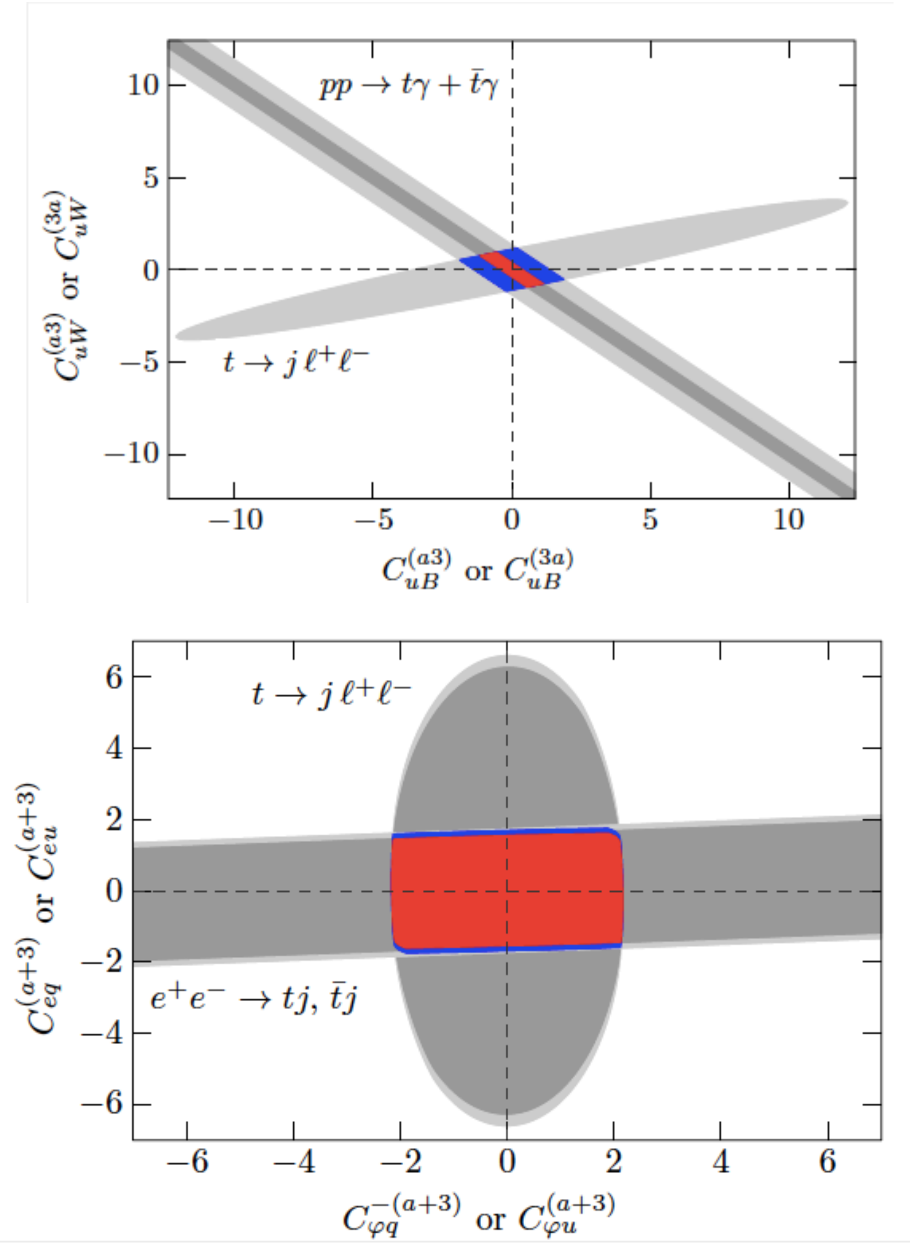
$$\sigma(e^+e^- \to tj + \bar{t}j) < 176 \text{ fb} \quad \text{at } \sqrt{s} = 207 \text{ GeV}$$ LEPII

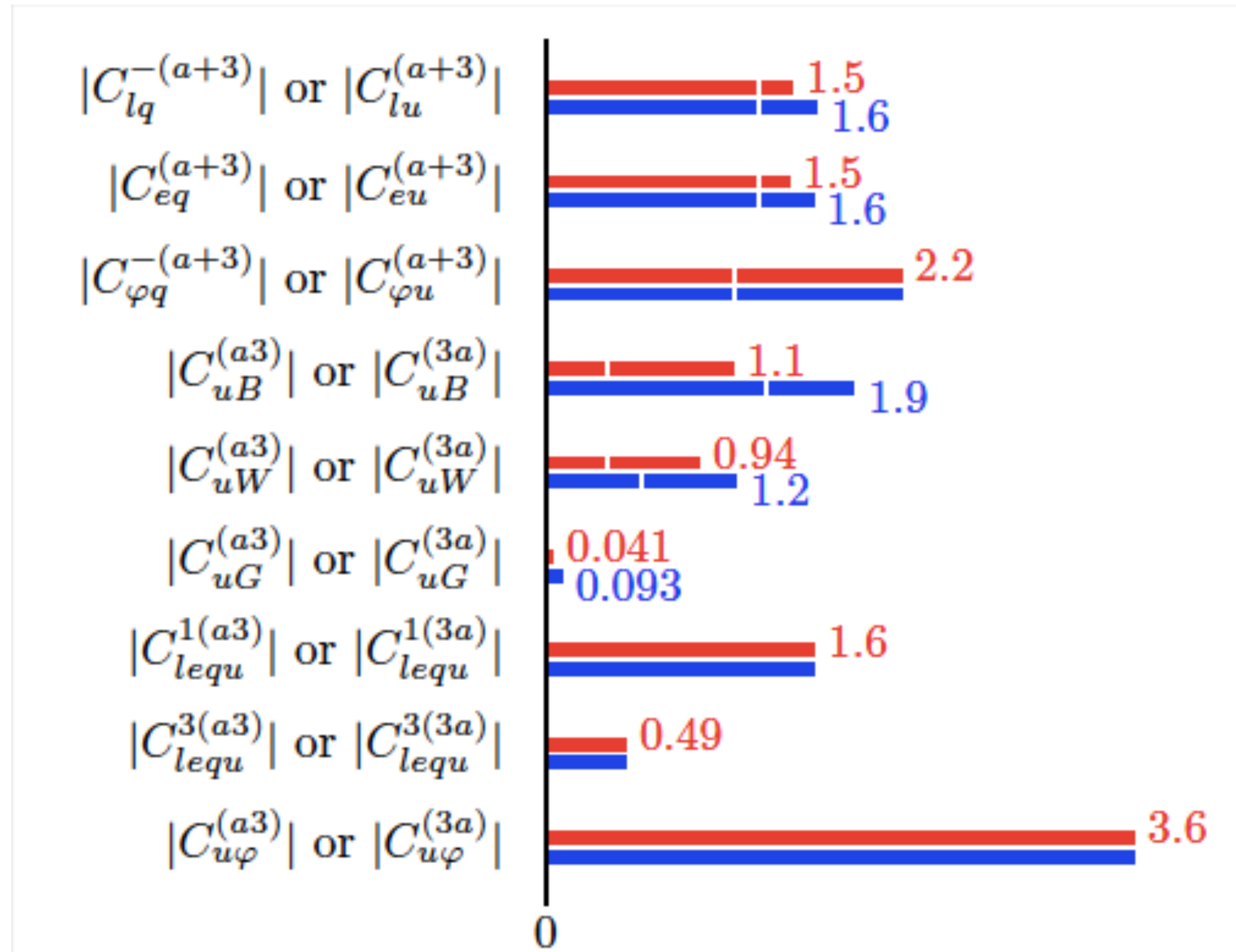


For the sake of illustration and simplicity, we only consider the most constraining observables. This suffices to set significant bounds on all two-quark operators as well as on a subset of the two-quark–two-lepton ones.

Top FCNC at NLO : global fit

[Durieux, FM, Zhang 2014]





First proof of principle that a complete global fitting strategy in a self-contained sector of the top EFT is possible with the available measurements. The red (blue) are for 1st (2nd) generation. Ticks = one on at the time.