EFT: the analysis approach and implementation in generators

Cen Zhang

BROOKHAVEN NATIONAL LABORATORY

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- Implementation status, UFO, MG5, Sherpa, Whizard. (Thank Silvan Kuttimalai and Jürgen Reuter)
- Available UFO models, results, etc…
- NLO status with MG5, HC and top-EFT.
- Summary

Approach

- SM Lagrangian supplemented with DIM-6 operators (hence SMEFT)

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

- The physics goal is to **determine the SM Lagrangian at Dim-6.**
- Determining the operators for measurements makes sense only if a **GLOBAL STRATEGY** is used. Ideally the following should be done:
  - Assume all ops might **NOT** be zero at the measured scale.
  - Identify operators entering each observables.
  - Find enough observables to constrain all ops.
  - Calculate observables. —- where we need tools
  - Solve the system.

  cf. ATL-PHYS-PUB-2015-047

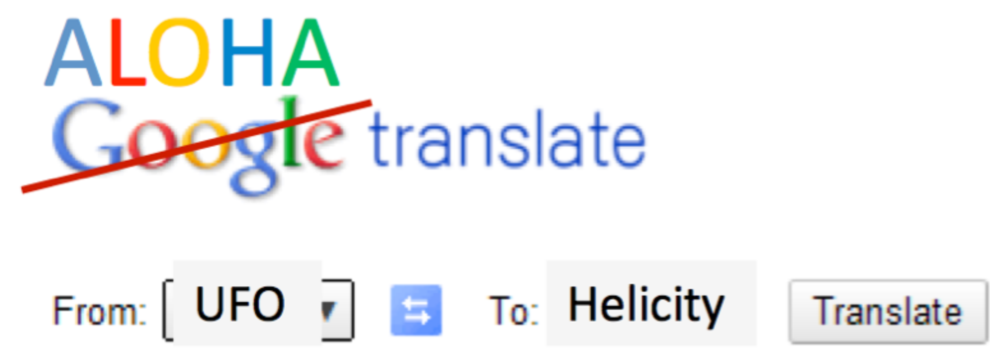
Status summary

EFT with MG5

- Simply follow:
  FeynRules->UFO->MG5

- <u>All higher-dimensional Lorentz structures are supported in **UFO**.</u>

[1108.2040 Degrande et al.]



- **ALOHA** translates Lorentz structures in UFO to helicity amplitude subroutines.

[1108.2041 de Aquino et al.]

- In principle this is it. <u>(At LO) all you can do with the SM can be done with higher-dim operators.</u> Except dynamical scales…

At <u>https://feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage</u> you can find a list of EFT models ready for use.

EFTs with Sherpa

Silvan Kuttimalai

Institute for Particle Physics Phenomenology, Durham

EFTs with UFO and Sherpa [arXiv:1412.6478]

UFO-support Fully Automatized via Python Extension

- Loads UFO model
- Writes out a C++ model
- Writes out C++ routines for arbitrary Lorentz structures
- Compiles everything, installs library to be loaded at runtime
- Once installed, model is available for event generation
- Use identical model and parameter input as e.g. MadGraph

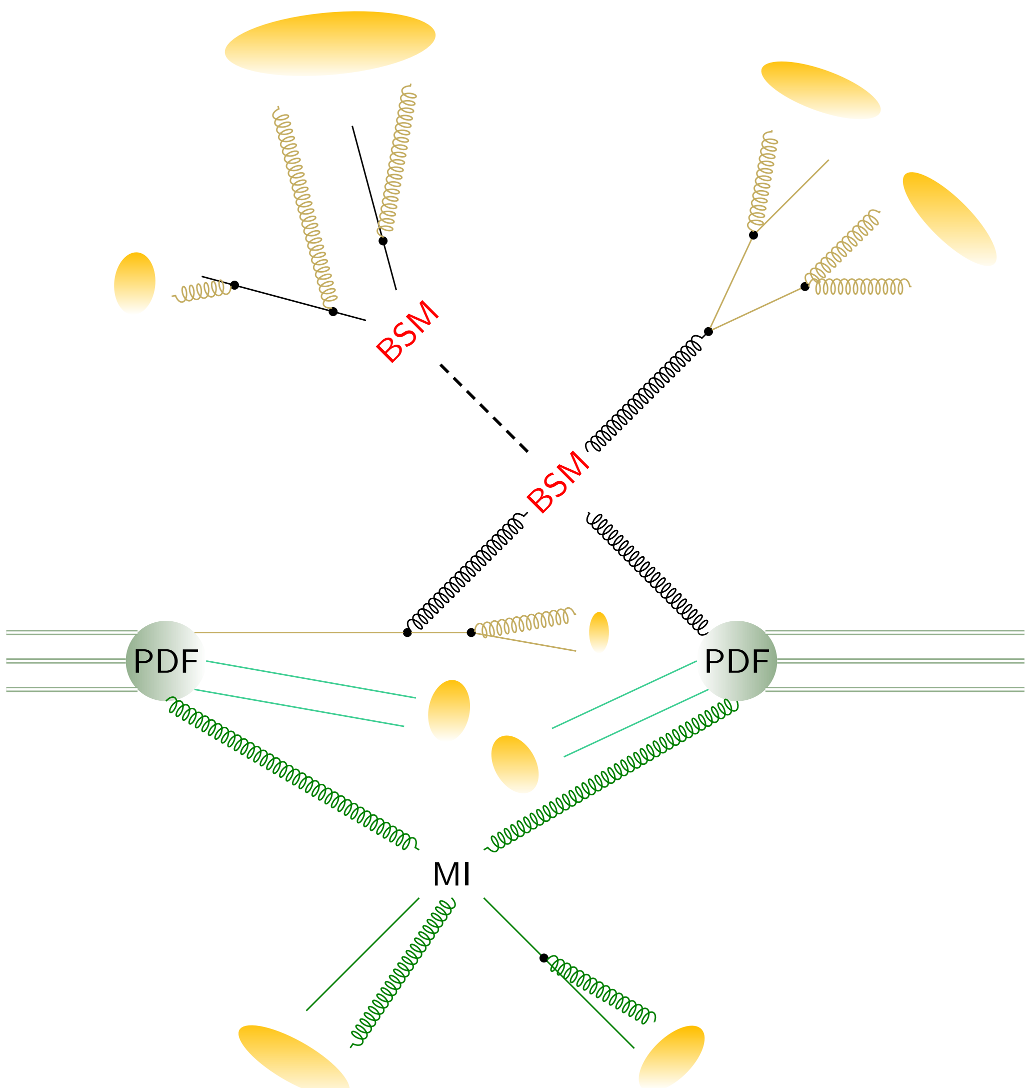
EFTs with UFO+Sherpa

- FeynRules/UFO accommodates very generic interactions
- Any EFT implemented in FeynRules/UFO can be simulated with Sherpa
- Arbitrary higher dimensional (EFT-) operators supported

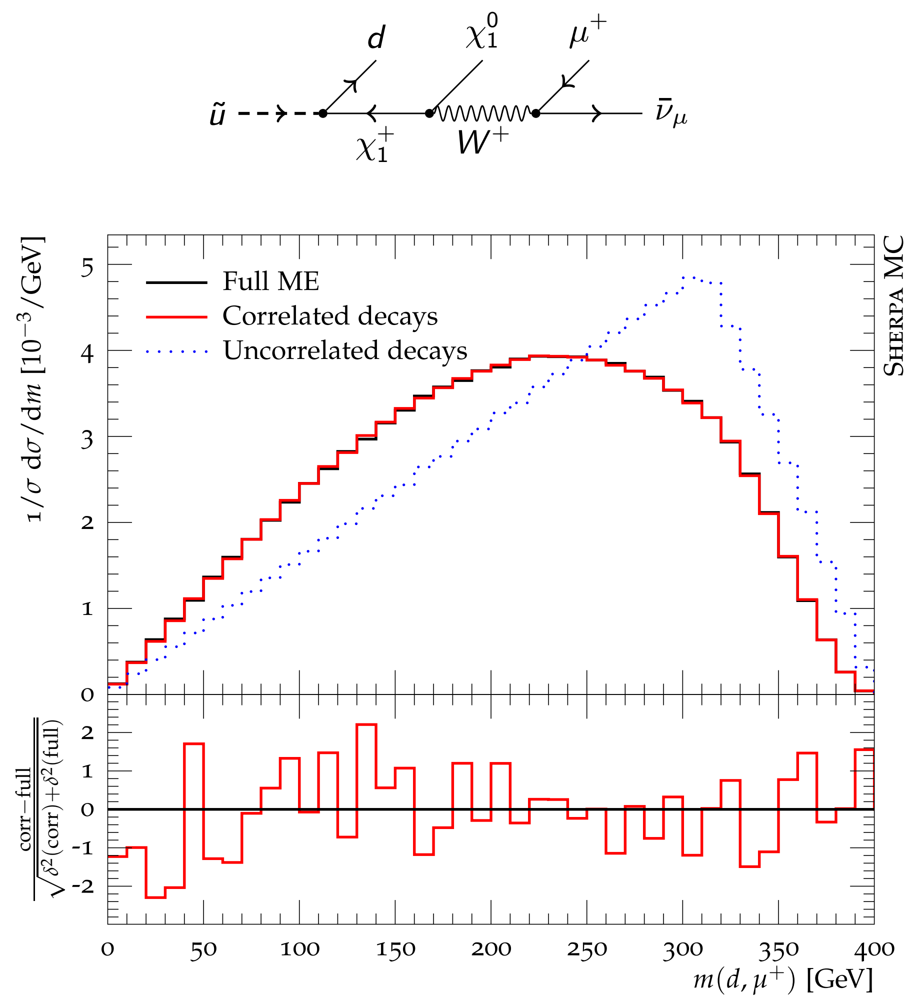
EFTs with UFO and Sherpa [arXiv:1412.6478]

UFO Support Seamlessly Integrated with Framework

- High multiplicity tree-level MEs with Comix for hard scattering
- Fully automatized spin-correlated decay chains
- Events can be showered and hadronized as usual



Example: MSSM Decays



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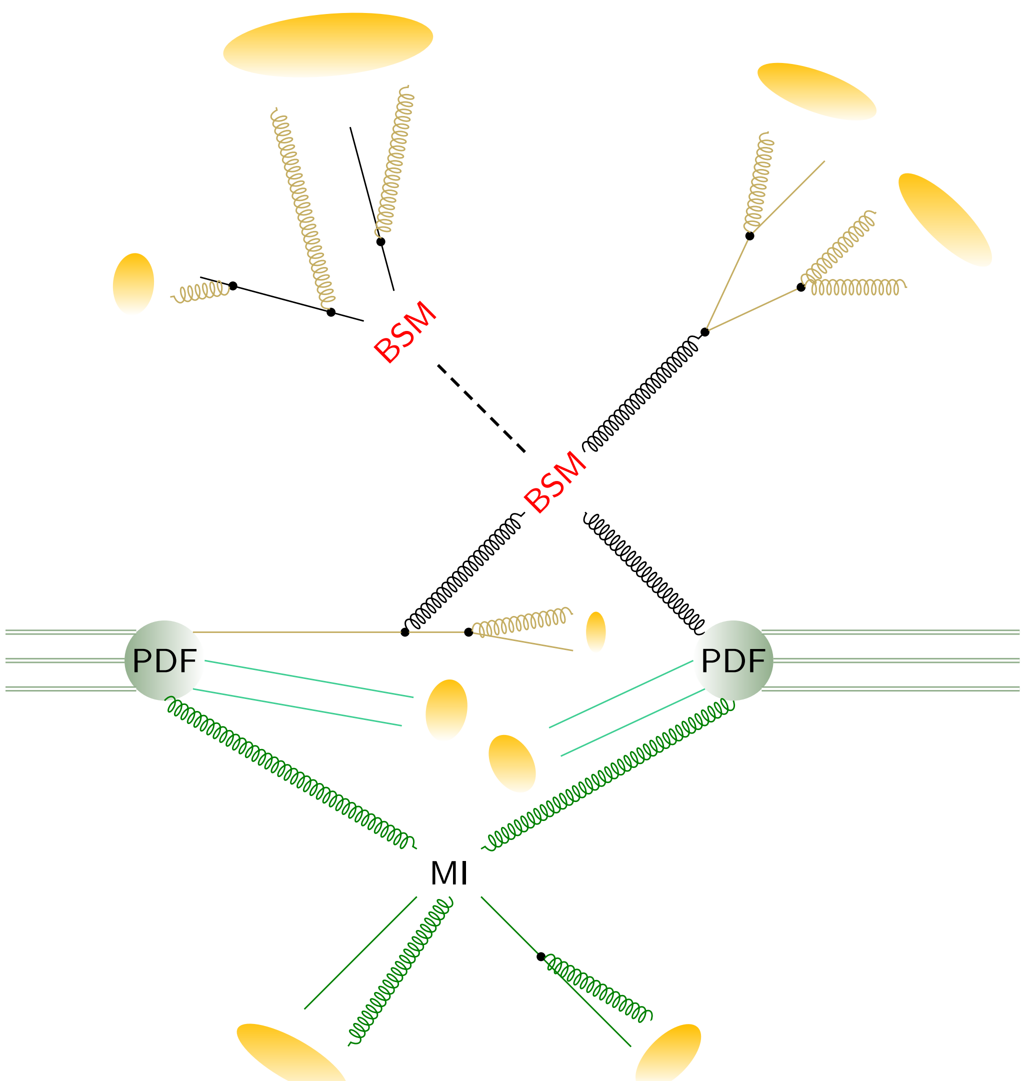

Current Development

- First EFT applications with tree-level merging
- First steps towards fixed-order NLO with OpenLoops

EFT with Whizard

(Thank Jürgen Reuter)

- Complete SM EFT at Dim-6 implemented in v2.2.8, in the Warsaw basis.

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[B. Grzadkowski et al, 2010]

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

EFT with Whizard

(Thank Jürgen Reuter)

- Complete SM EFT at Dim-6 implemented in v2.2.8, in the Warsaw basis.

- Some Dim-8 operators are available (quartic weak-boson couplings).

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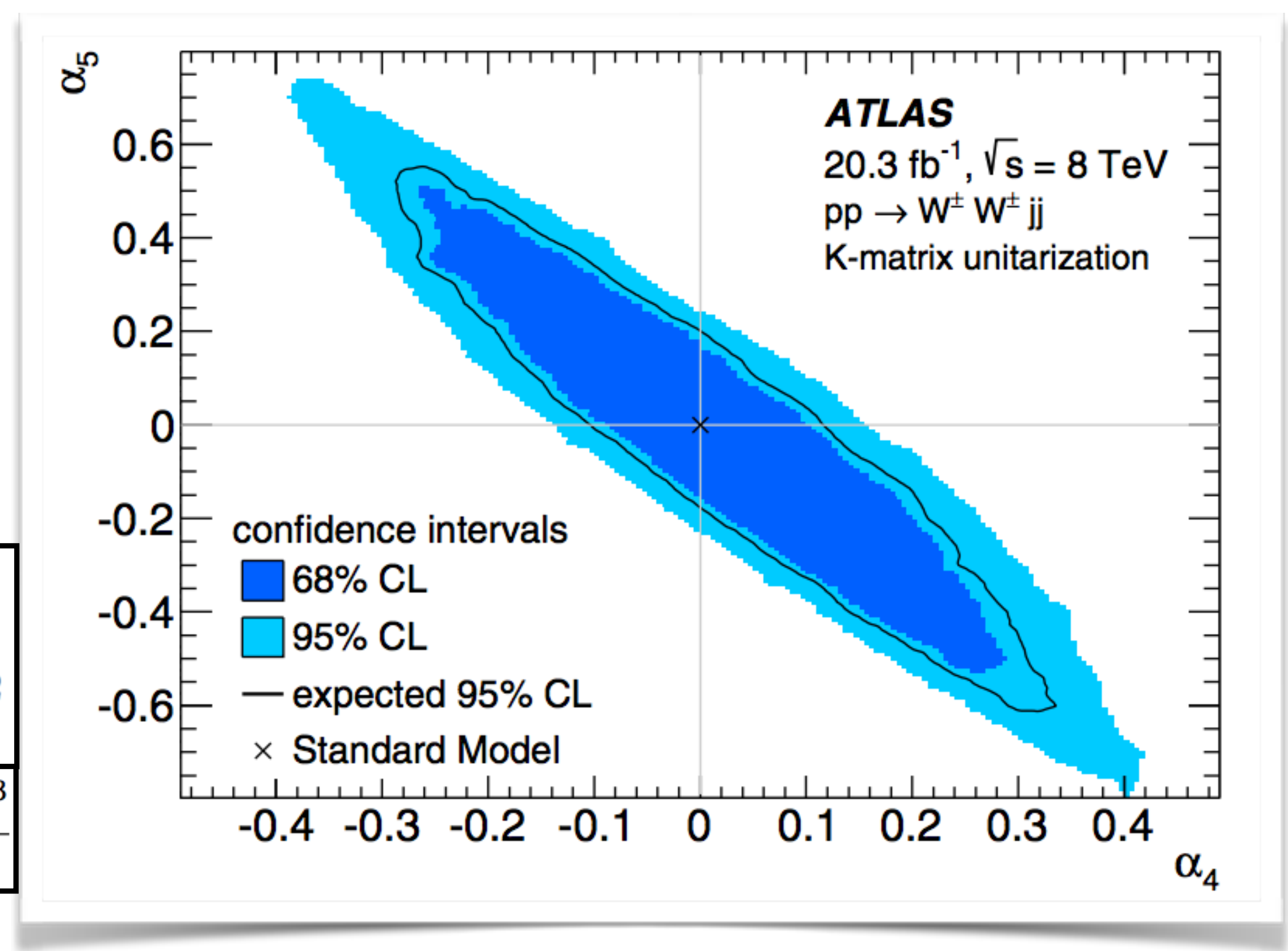
[1405.6241]



$$\mathcal{L}_4^{(4)} = \alpha_4 \left[\mathrm{Tr}\left(V_\mu V_\nu\right)\right]^2$$
$$\mathcal{L}_5^{(4)} = \alpha_5 \left[\mathrm{Tr}\left(V_\mu V^\mu\right)\right]^2$$

$$\mathbf{V}_\mu \hat{=} -\mathrm{i}g W_\mu^a \frac{\tau^a}{2} + \mathrm{i}g' B_\mu \frac{\tau^3}{2}$$

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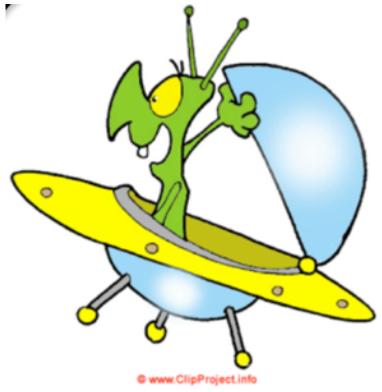
- UFO not yet supported but in progress. (at latest in summer.)

UFO examples

That are:

- publicly available
- validated
- ready for simulation



Multi-vector boson

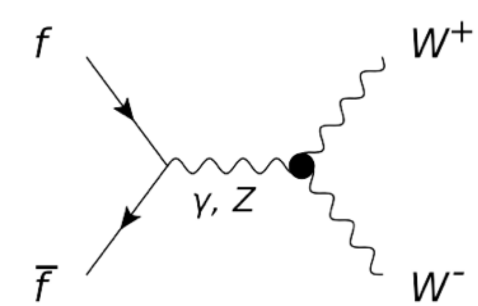
- Dim-6 TGC: UFO and VBFNLO
  - UFO model: EWdim6 https://feynrules.irmp.ucl.ac.be/wiki/EWdim6
    [arXiv:1205.4231, Degrande, Greiner, Kilian, Mattelaer, Mebane, Stelzer, Willenbrock, CZ]

CP-even

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}]$$
$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi),$$

CP-odd

$$\mathcal{O}_{\tilde{W}WW} = \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}]$$
$$\mathcal{O}_{\tilde{W}} = (D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi),$$



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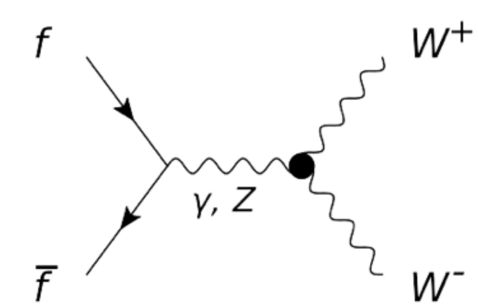
CP-odd

$$\mathcal{O}_{\tilde{W}WW} = \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}]$$
$$\mathcal{O}_{\tilde{W}} = (D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi),$$

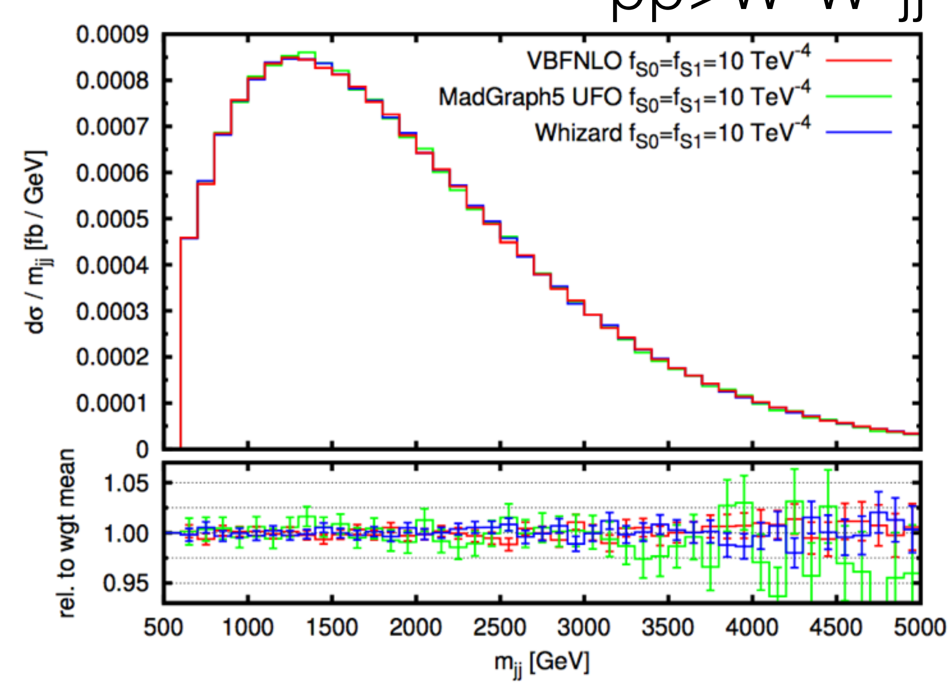


- Dim-8 QGC: UFO, Whizard, VBFNLO

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

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$			X			X	X	X	X

pp>W+W+jj



[1309.7890, C. Degrande et al.]

Top EFT

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

Top effective theory

Author

Céline Degrande

- University of Illinois at Urbana Champaign
- cdegrand@...

Description of the model & reference

The top effective theory model contains all the dimension-six operators affecting top pair production, single top pair production and top decay by interfering with the SM amplitudes.

Phys.Rev. D83 (2011) 034006: S. Willenbrock, C. Zhang, *Effective-Field-Theory Approach to Top-Quark Production and Decay.*

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The top effective theory model con
production, single top pair product

Phys.Rev. D83 (2011) 034006:
Top-Quark Production and Decay.

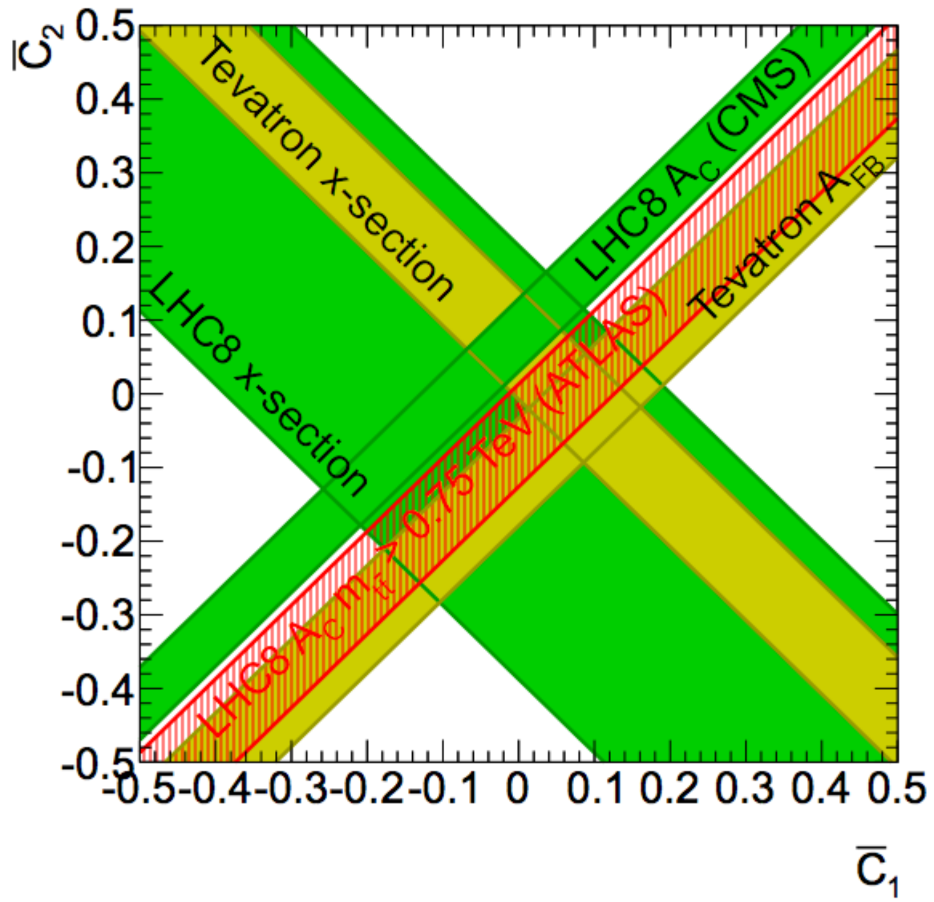
operator	process
$O_{\phi q}^{(3)} = i(\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$	top decay, single top
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu}$ (with real coefficient)	top decay, single top
$O_{qq}^{(1,3)} = (\bar{q}^i \gamma_\mu \tau^I q^j)(\bar{q}\gamma^\mu \tau^I q)$	single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu}$ (with real coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_G = f_{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$gg \to t\bar{t}$
$O_{\phi G} = \frac{1}{2}(\phi^+ \phi) G^A_{\mu\nu} G^{A\mu\nu}$	$gg \to t\bar{t}$
7 four-quark operators	$q\bar{q} \to t\bar{t}$
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu}$ (with imaginary coefficient)	top decay, single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu}$ (with imaginary coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$

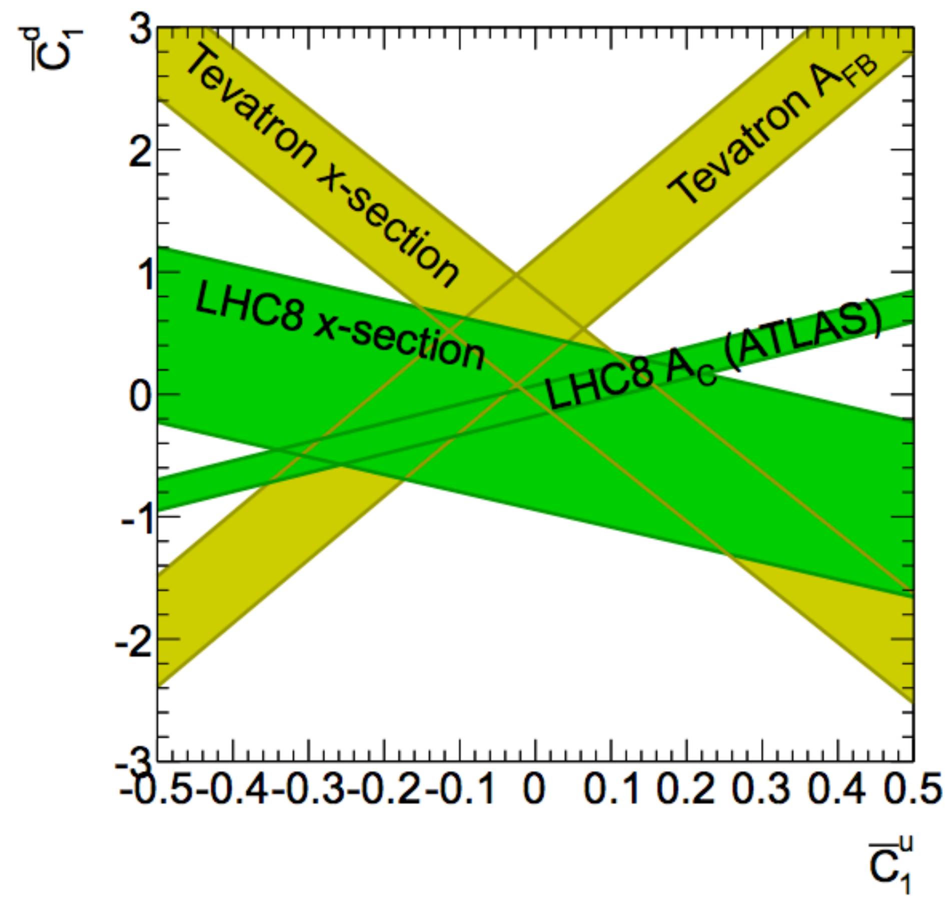
Top EFT

[1512.07542 Perello Rosello, Vos]

	SM prediction	Measurement
Tevatron, 1.96 TeV $p\bar{p}$, CDF+D0, x-section	7.16 ± 0.26 pb [24]	7.60 ± 0.41 pb [25]
Tevatron, 1.96 1.96 TeV $p\bar{p}$, CDF+D0, A_{FB}	$9.5 \pm 0.7\%$ [9]	$13 \pm 2.3\%$ [4, 5]
LHC, 8 TeV pp, CMS+ATLAS inclusive σ	245.80 ± 10.56 pb [24]	241.50 ± 8.54 pb [26]
ATLAS 8 TeV pp, inclusive A_C	$1.11 \pm 0.04\%$ [27]	$0.9 \pm 0.5\%$ [28]
CMS 8 TeV pp, inclusive A_C	$1.11 \pm 0.04\%$ [27]	$0.3 \pm 0.4\%$ [15]
ATLAS 8 TeV pp, differential A_C ($m_{t\bar{t}} > 0.75$ TeV)	$1.60 \pm 0.04\%$ [29]	$4.2 \pm 3.2\%$ [30]

Table 2 Datasets used in the fit. The Tevatron A_{FB} measurement corresponds to a naive approximation between D0 and CDF experiments [31]. A combination of the ATLAS and CMS measurements of the inclusive asymmetry at 8 TeV is not yet available, so both measurement are kept as independent constraints.





Higgs Eff. Lagrangian

feynrules.irmp.ucl.ac.be/wiki/HEL

Higgs effective Lagrangian ¶

Authors

Adam Alloul

- Groupe de Recherche en Physique des Hautes Energies - Universite de Haute Alsace
- adam.alloul@...

Benjamin Fuks

- CERN / Institut Pluridisciplinaire Hubert Curien / Universite de Strasbourg
- benjamin.fuks@...

Veronica Sanz

- University of Sussex
- v.sanz@...

Description of the model & references

The model we have implemented is based on the description given here and on the parametrization adopted here. The Lagrangian consists of an extension of the SM Lagrangian with terms of dimension up to six comprising

- the set of CP-conserving operators describing the strongly interacting Higgs Lagrangian declared as LSILH in the model file;
- the set of operators describing the interactions of a pair of Higgs fields with a pair of leptons or quarks declared as LF1 in the model file;
- the set of operators describing the interactions of a single Higgs field with a pair of leptons or quarks and a gauge boson declared as LF2 in the model file;
- the set of operators affecting the gauge sector and possibly modifying the gauge boson self-energies and self-interactions. The variable corresponding to this piece of the Lagrangian is LBosons;
- the set of CP-violating operators declared in the variable LCP.

[arXiv:1310.5150, Alloul, Fuks, Sanz] [arXiv:1303.3876, Contino et al.]

- 33 CP-even + 6 CP-odd
- 34 operators relevant for Higgs
- Flavor-universal
- SILH: hep-ph/0703164, Guildice et al.
- F1: W/Z to ffbar (V/A)
- F2: EW/chromo-dipoles
- G: Gauge-boson self interaction

$$\Delta\mathcal{L}_{SILH} = \frac{\bar{c}_H}{2v^2}\,\partial^\mu(H^\dagger H)\,\partial_\mu(H^\dagger H) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\,(H^\dagger H)^3$$
$$+ \left(\left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R\right) + h.c.\right)$$
$$+ \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger\sigma^i\overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger\overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$
$$+ \frac{i\bar{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$
$$+ \frac{\bar{c}_\gamma\,g'^2}{m_W^2}\,H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}\,,$$

$$\Delta\mathcal{L}_{F_1} = \frac{i\bar{c}_{Hq}}{v^2}\,(\bar{q}_L\gamma^\mu q_L)\,(H^\dagger\overleftrightarrow{D}_\mu H) + \frac{i\bar{c}'_{Hq}}{v^2}\,(\bar{q}_L\gamma^\mu\sigma^i q_L)\,(H^\dagger\sigma^i\overleftrightarrow{D}_\mu H)$$
$$+ \frac{i\bar{c}_{Hu}}{v^2}\,(\bar{u}_R\gamma^\mu u_R)\,(H^\dagger\overleftrightarrow{D}_\mu H) + \frac{i\bar{c}_{Hd}}{v^2}\,(\bar{d}_R\gamma^\mu d_R)\,(H^\dagger\overleftrightarrow{D}_\mu H)$$
$$+ \left(\frac{i\bar{c}_{Hud}}{v^2}\,(\bar{u}_R\gamma^\mu d_R)\,(H^{c\,\dagger}\overleftrightarrow{D}_\mu H) + h.c.\right)$$
$$+ \frac{i\bar{c}_{HL}}{v^2}\,(\bar{L}_L\gamma^\mu L_L)\,(H^\dagger\overleftrightarrow{D}_\mu H) + \frac{i\bar{c}'_{HL}}{v^2}\,(\bar{L}_L\gamma^\mu\sigma^i L_L)\,(H^\dagger\sigma^i\overleftrightarrow{D}_\mu H)$$
$$+ \frac{i\bar{c}_{Hl}}{v^2}\,(\bar{l}_R\gamma^\mu l_R)\,(H^\dagger\overleftrightarrow{D}_\mu H)\,,$$

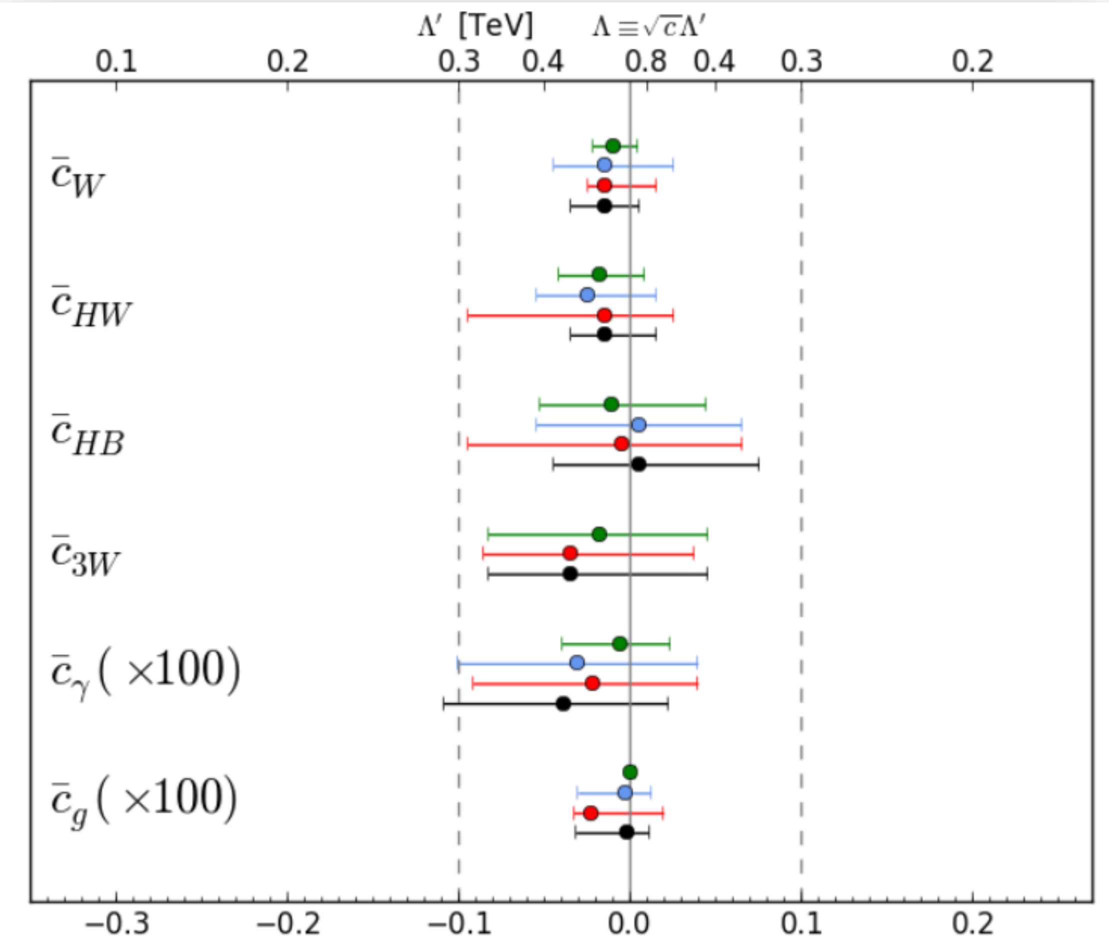
$$\Delta\mathcal{L}_{F_2} = \frac{\bar{c}_{uB}\,g'}{m_W^2}\,y_u\,\bar{q}_L H^c\sigma^{\mu\nu}u_R\,B_{\mu\nu} + \frac{\bar{c}_{uW}\,g}{m_W^2}\,y_u\,\bar{q}_L\sigma^i H^c\sigma^{\mu\nu}u_R\,W^i_{\mu\nu} + \frac{\bar{c}_{uG}\,g_S}{m_W^2}\,y_u\,\bar{q}_L H^c\sigma^{\mu\nu}\lambda^a u_R\,G^a_{\mu\nu}$$
$$+ \frac{\bar{c}_{dB}\,g'}{m_W^2}\,y_d\,\bar{q}_L H\sigma^{\mu\nu}d_R\,B_{\mu\nu} + \frac{\bar{c}_{dW}\,g}{m_W^2}\,y_d\,\bar{q}_L\sigma^i H\sigma^{\mu\nu}d_R\,W^i_{\mu\nu} + \frac{\bar{c}_{dG}\,g_S}{m_W^2}\,y_d\,\bar{q}_L H\sigma^{\mu\nu}\lambda^a d_R\,G^a_{\mu\nu}$$
$$+ \frac{\bar{c}_{lB}\,g'}{m_W^2}\,y_l\,\bar{L}_L H\sigma^{\mu\nu}l_R\,B_{\mu\nu} + \frac{\bar{c}_{lW}\,g}{m_W^2}\,y_l\,\bar{L}_L\sigma^i H\sigma^{\mu\nu}l_R\,W^i_{\mu\nu} + h.c.$$

$$\mathcal{L}_G = \frac{g^3\,\bar{c}_{3W}}{m_W^2}\epsilon_{ijk}W^i_{\mu\nu}W^{\nu j}{}_\rho W^{\rho\mu k} + \frac{g_s^3\,\bar{c}_{3G}}{m_W^2}f_{abc}G^a_{\mu\nu}G^{\nu b}{}_\rho G^{\rho\mu c} + \frac{\bar{c}_{2W}}{m_W^2}D^\mu W^k_{\mu\nu}D_\rho W_k^{\rho\nu}$$
$$+ \frac{\bar{c}_{2B}}{m_W^2}\partial^\mu B_{\mu\nu}\partial_\rho B^{\rho\nu} + \frac{\bar{c}_{2G}}{m_W^2}D^\mu G^a_{\mu\nu}D_\rho G_a^{\rho\nu}\,,$$

(4-fermions are not included)

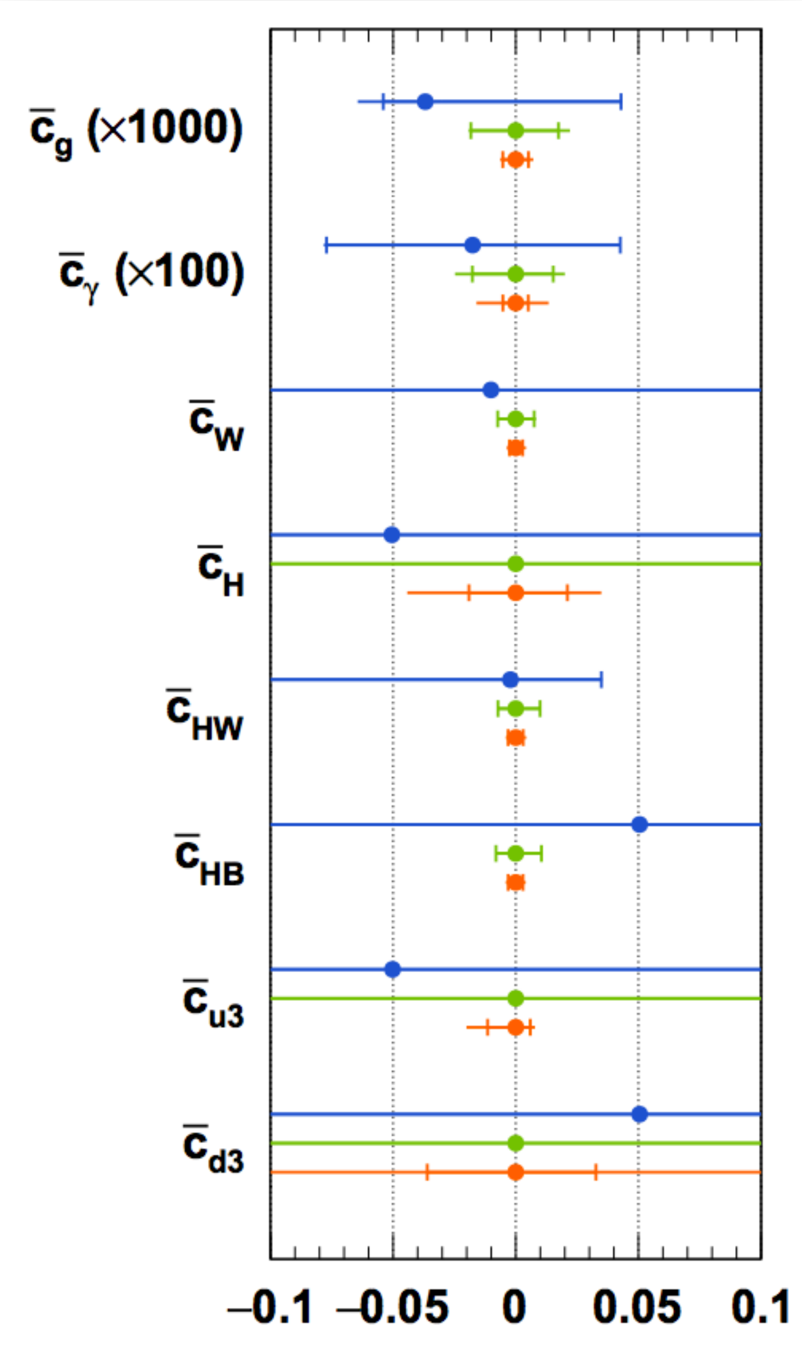
HEL in Higgs Fits

[1404.3667,1410.7703 Ellis, Sanz, You]



Higgs, TGC, combination

see also
[1511.0517 Englert, Kogler, Schulz, Spannowsky]



Current, 300fb^{-1}, 3000fb^{-1}
TGC not included

EW sector probed by PEWM+TGC+Higgs: 8+3+8

assuming flavor symmetry

1. PEWM

$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ (+) $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
$\mathcal{O}^{(3)\,l}_{LL} = (\bar{L}_L\sigma^a\gamma^\mu L_L)\,(\bar{L}_L\sigma^a\gamma_\mu L_L)$
$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$
$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$
$\mathcal{O}^{(3)\,q}_L = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\sigma^a\gamma^\mu Q_L)$
$\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$

Mainly from Z-pole: only 8 d.o.f
(10 would appear in BW/Warsaw)

[A. Falkowski and F. Riva 2014]

2. TGC (and Higgs)

$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ (-) $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$
$\mathcal{O}_{3W} = \frac{1}{3!}g\epsilon_{abc}W^{a\,\nu}_{\mu}W^b_{\nu\rho}W^{c\,\rho\mu}$

W-pair production: $g_1^Z,\ \kappa_\gamma,\ \lambda_Z$

3. **New from Higgs**

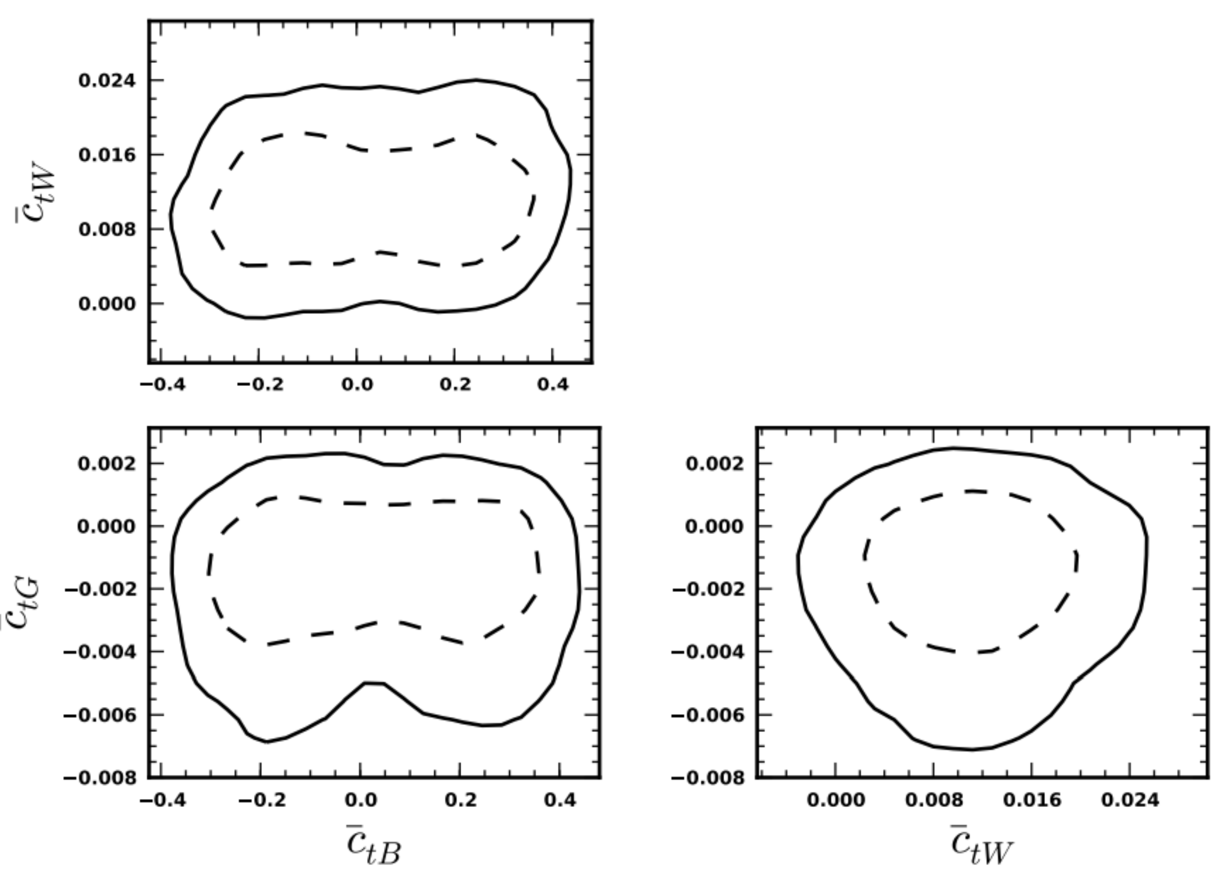
$\mathcal{O}_H = [\partial_\mu(H^\dagger H)]^2$
$\mathcal{O}_{BB} = \frac{g'^2}{4}\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{WW} = \frac{g^2}{4}\lvert H\rvert^2 W^a_{\mu\nu}W^{a\mu\nu}$
$\mathcal{O}_{GG} = \frac{g_s^2}{4}\lvert H\rvert^2 G^A_{\mu\nu}G^{A\mu\nu}$
$\mathcal{O}_{y_u} = y_u\lvert H\rvert^2\bar{Q}_L\widetilde{H}u_R$
$\mathcal{O}_{y_d} = y_d\lvert H\rvert^2\bar{Q}_L H d_R$
$\mathcal{O}_{y_e} = y_e\lvert H\rvert^2\bar{L}_L H e_R$
$\mathcal{O}_6 = \lambda\lvert H\rvert^6$

HEL in Top Fits

[1404.2581, Tonero and Rosenfeld]

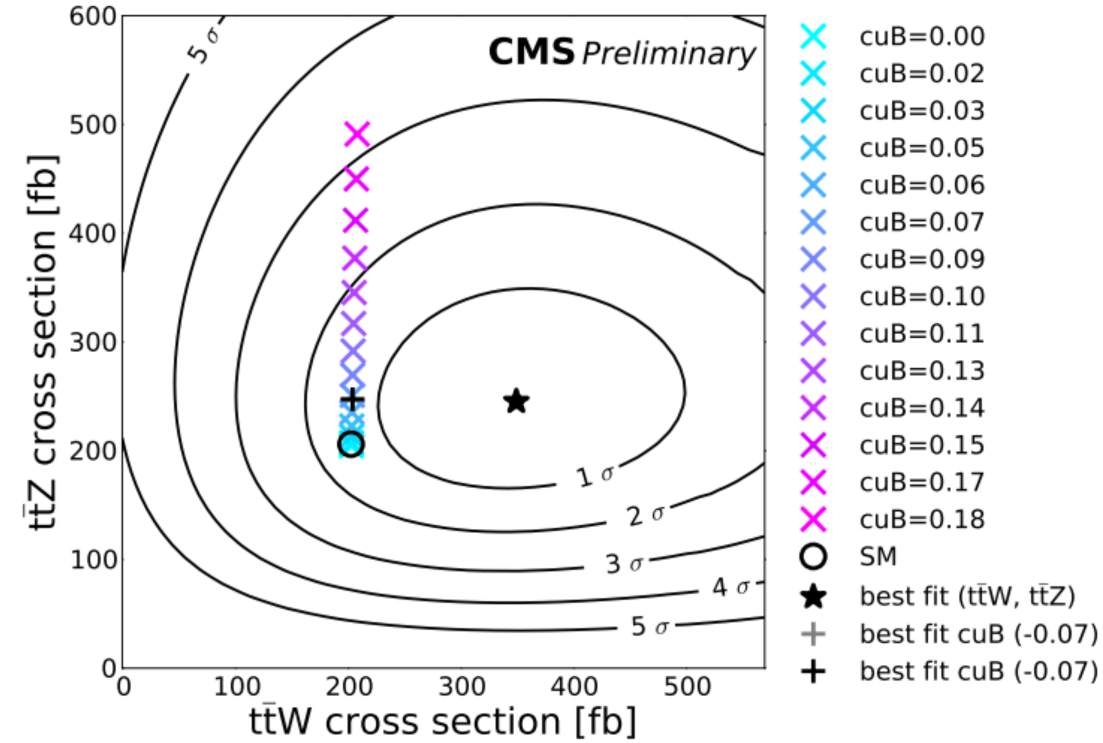
Top dipole fits

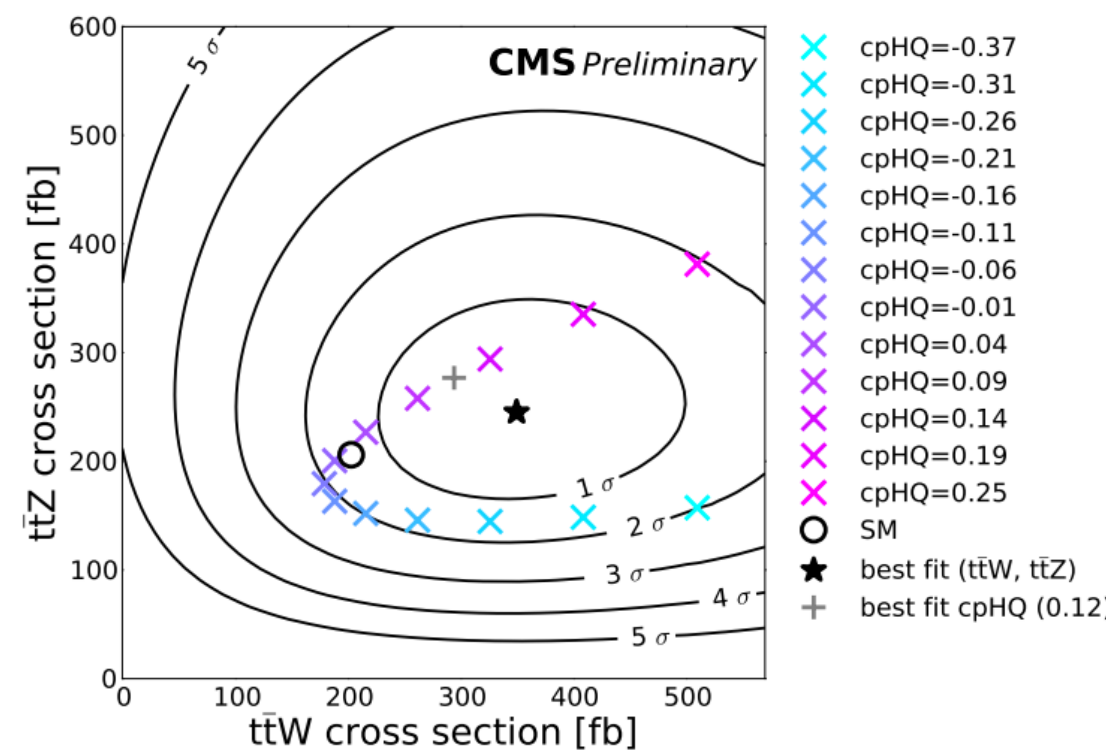
LHC observables	Experimental value
$t\bar{t}V$ production	$0.43^{+0.17}_{-0.15}$ pb [16]
Single top t-channel	67.2 ± 6.1 pb [19]
tW production	23.4 ± 5.4 pb [21]
$t\bar{t}$ production	237.7 ± 1.7(stat)± 7.4(syst)$\pm$ 7.4 (lumi) ± 4.0 (energy) pb [23]
W helicity fractions	$F_0 = 0.626 \pm 0.034$ (stat.) ± 0.048 (syst.) $F_L = 0.359 \pm 0.021$ (stat.) ± 0.028 (syst.) $F_R = 0.015 \pm 0.034$ [25]



CMS PAS TOP-14-021

ttZ+ttW





…and many more

- Check the FeynRules model database
https://feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage

- E.g.

  - **nTGC**: [C. Degrande]
  dim-8 operators affecting neutral triple gauge boson couplings

  - **Higgs Characterisation**: [F. Demartin, K. Mawatari]
  spin/parity characterisation of the 125 GeV scalarresonance.

  - **Higgs basis** [B. Fuks, K. Mawatari]

  - There are also some top- and Higgs-FCNC models

- Also check
Rosetta: an operator basis translator for SM EFT [1508.05895, Falkowski et al.]
(Warsaw, SILH, Higgs basis, …)

Going to NLO in QCD with EFT

- With MADGRAPH5_AMC@NLO, all we need for EFT @ NLO is the Dim-6 UV and R2 counterterms.
  - UV CT characterize the RG running & mixing of operators.
  - R2 occurs due to numerical techniques only evaluate 4-dimensional part of loop amplitude (while we need D-dimensional)
- **NLOCT** is being developed to incorporate both at Dim-6, in an automatic way. *[C. Degrande 2014]*
- Alternatively, there are case studies, not fully automated. For example, can take UV CTs from [1312.2014 Alonso et al.]
- Several NLO UFOs have been made available.

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

  - **Higgs Characterisation** *[P. Artoisenet et al. 2013]* *[F. Demartin et al. 2014]* *[F. Demartin et al. 2015]*
  - **HEL @ NLO** in progress (Degrande, Fuks, Mawatari, Mimasu, Sanz)
  - **Top EFTs** (Bylund, Degrande, Franzosi, Maltoni, Tsinikos, Vryonidou, CZ)
  - Color Neutral ops trivial to add (TGC, DM with vectors, etc.)

Higgs Characterisation

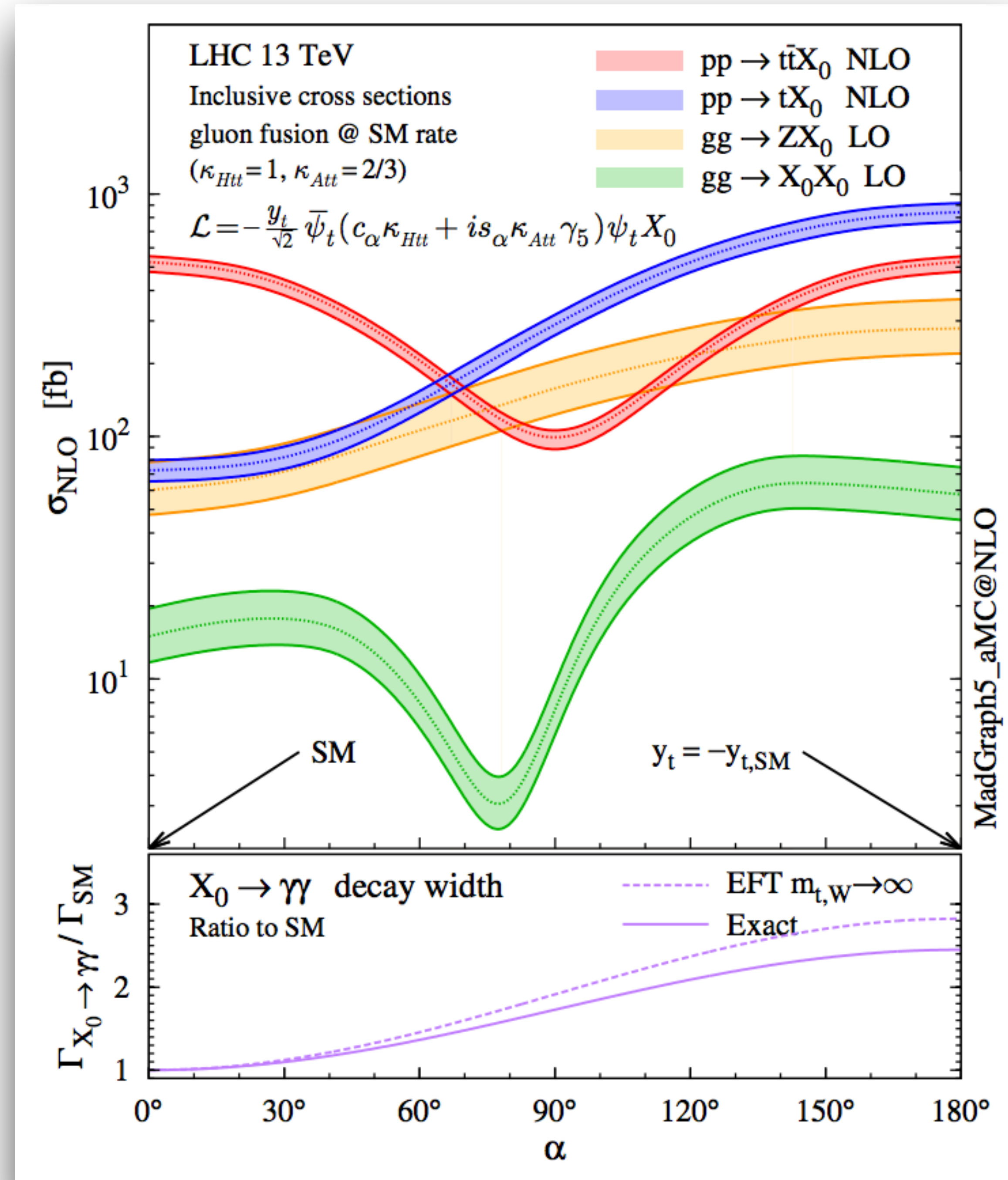
https://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation

[P. Artoisenet et al. 2013] [F. Demartin et al. 2014] [F. Demartin et al. 2015]

$$\mathcal{L}_0^f = -\sum_{f=t,b,\tau} \bar{\psi}_f \left(c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aff} g_{Aff} \gamma_5 \right) \psi_f X_0$$

$$\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{\rm SM} \left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] \\
& - \tfrac{1}{4} \left[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma} A_{\mu\nu} \widetilde{A}^{\mu\nu} \right] \\
& - \tfrac{1}{2} \left[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma} Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma} Z_{\mu\nu} \widetilde{A}^{\mu\nu} \right] \\
& - \tfrac{1}{4} \left[c_\alpha \kappa_{Hgg} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg} G_{\mu\nu}^a \widetilde{G}^{a,\mu\nu} \right] \\
& - \tfrac{1}{4} \tfrac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \widetilde{Z}^{\mu\nu} \right] \\
& - \tfrac{1}{2} \tfrac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \widetilde{W}^{-\mu\nu} \right] \\
& - \tfrac{1}{\Lambda} c_\alpha \Big[\kappa_{H\partial\gamma} A_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z} Z_\nu \partial_\mu Z^{\mu\nu} \\
& \qquad + \left(\kappa_{H\partial W} W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c. \right) \Big] \Big\} X_0
\end{aligned}$$

parameter	description
Λ [GeV]	cutoff scale
c_α ($\equiv \cos\alpha$)	mixing between 0^+ and 0^-
κ_i	dimensionless coupling parameter



Higgs Characterisation

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

[P. Artoisenet et al. 2013] [F. Demartin et al. 2014] [F. Demartin et al. 2015]

$$\mathcal{L}_0^f = -\sum_{f=t,b,\tau} \bar\psi_f \big(c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aff} g_{Aff}\,\gamma_5\big)\psi_f X_0$$

$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{\rm SM}\big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W^+_\mu W^{-\mu}\big]$$

$$-\frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu}\widetilde{A}^{\mu\nu}\big]$$

$$-\frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu}A^{\mu\nu} \ldots$$

$$-\frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu}G^{a,\mu\nu} \ldots$$

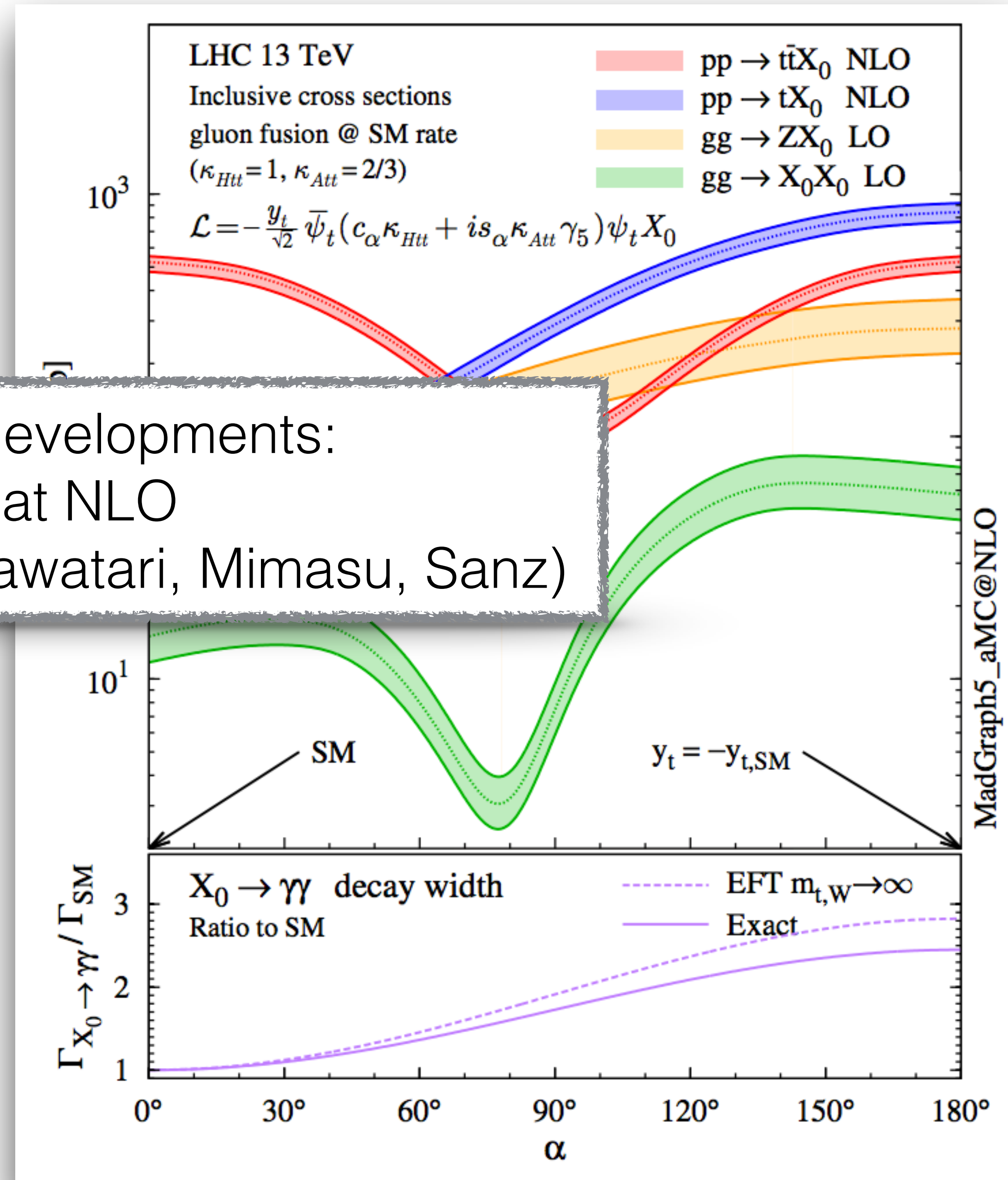
$$-\frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu} \ldots$$

$$-\frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu}\widetilde{W}^{-\mu\nu}\big]$$

$$-\frac{1}{\Lambda} c_\alpha \big[\kappa_{H\partial\gamma}\, A_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu}$$

$$+ \big(\kappa_{H\partial W} W^+_\nu \partial_\mu W^{-\mu\nu} + h.c.\big)\big]\Big\} X_0$$

parameter	description
Λ [GeV]	cutoff scale
c_α $(\equiv \cos\alpha)$	mixing between 0^+ and 0^-
κ_i	dimensionless coupling parameter



On going developments:
HEL at NLO
(Degrande, Fuks, Mawatari, Mimasu, Sanz)

Top EFT

Flavor-conserving

Process	O_{tG}	O_{tB}	O_{tW}	$O^{(3)}_{\varphi Q}$	$O^{(1)}_{\varphi Q}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	X		X	X				X		
$pp \to t\tilde{q}$	X		X	X				X		
$pp \to tW$	X		X	X				X	X	X
$pp \to t\bar{t}$	X						X	X	X	X
$pp \to t\bar{t}\gamma$	X	X	X				X	X	X	X
$pp \to t\gamma j$	X	X	X					X		
$pp \to t\bar{t}Z$	X	X	X	X	X	X	X	X	X	X
$pp \to tZj$	X	X	X	X	X	X		X		
$pp \to t\bar{t}h$	X						X	X	X	X
$pp \to t\bar{j}h$	X						X	X		X
$gg \to H, HZ$	X			X	X	X	X			X

Flavor-changing (neutral)

Process	$O^{(3)}_{\phi q}$	$O^{(1)}_{\phi q}$	$O^{(1)}_{\phi u}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to qZ^*, \gamma^* \to ql^+l^-$	X	X	X	X	X	X		X
$t \to q\gamma$				X	X	X		
$t \to qH$						X	X	
$pp \to t$						X		X
$pp \to tZ$	X	X	X	X	X	X		X
$pp \to t\gamma$				X	X	X		X
$pp \to tH$						X	X	X

We aim to provide: (in particular for experimentalists)

- A framework for testing **top-quark couplings**, with **QCD NLO** accuracy.
- i.e. all TH inputs for an NLO global fit will be **automated**.

Flavor-conserving

Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	$O_{4\text{f}}$	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	X		X	X				X		
$pp \to t\tilde{q}$	X		X	X				X		
$pp \to tW$	X		X	X				X	X	X
$pp \to t\bar{t}$	X						X	X	X	X
$pp \to t\bar{t}\gamma$	X	X	X				X	X	X	X
$pp \to t\gamma j$	X	X	X					X		
$pp \to t\bar{t}Z$	X	X	X	X	X	X	X	X	X	X
$pp \to tZj$	X	X	X	X	X	X		X		
$pp \to t\bar{t}h$	X						X	X	X	X
$pp \to t\bar{j}h$	X						X	X		X
$gg \to H, HZ$	X			X	X	X	X			X

Flavor-changing (neutral)

Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	$O_{4\text{f}}$
$t \to qZ^*, \gamma^* \to ql^+l^-$	X	X	X	X	X	X		X
$t \to q\gamma$				X	X	X		
$t \to qH$						X	X	
$pp \to t$						X		X
$pp \to tZ$	X	X	X	X	X	X		X
$pp \to t\gamma$				X	X	X		X
$pp \to tH$						X	X	X

- Decays and FCNC direct t production is available analytically.
[1404.1264 CZ], [1305.7386 F. Maltoni, CZ], [hep-ph/0508016 J.J.Liu et al.]

Flavor-conserving

Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	$O_{4\text{f}}$	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	X		X	X				X		
$pp \to t\tilde{q}$	X		X	X				X		
$pp \to tW$	X		X	X				X	X	X
$pp \to t\bar{t}$	X						X	X	X	X
$pp \to t\bar{t}\gamma$	X	X	X				X	X	X	X
$pp \to t\gamma j$	X	X	X					X		
$pp \to t\bar{t}Z$	X	X	X	X	X	X	X	X	X	X
$pp \to tZj$	X	X	X	X	X	X		X		
$pp \to t\bar{t}h$	X						X	X	X	X
$pp \to t\bar{j}h$	X						X	X		X
$gg \to H, HZ$	X			X	X	X	X			X

Flavor-changing (neutral)

Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	$O_{4\text{f}}$
$t \to qZ^*, \gamma^* \to ql^+l^-$	X	X	X	X	X	X		X
$t \to q\gamma$				X	X	X		
$t \to qH$						X	X	
$pp \to t$						X		X
$pp \to tZ$	X	X	X	X	X	X		X
$pp \to t\gamma$				X	X	X		X
$pp \to tH$						X	X	X

- Decays and FCNC direct t production is available analytically.
  [1404.1264 CZ], [1305.7386 F. Maltoni, CZ], [hep-ph/0508016 J.J.Liu et al.]
- FCNC associated productions have been implemented.
  [1412.5594 Degrande, Maltoni, Wang, CZ] http://feynrules.irmp.ucl.ac.be/wiki/TopFCNC

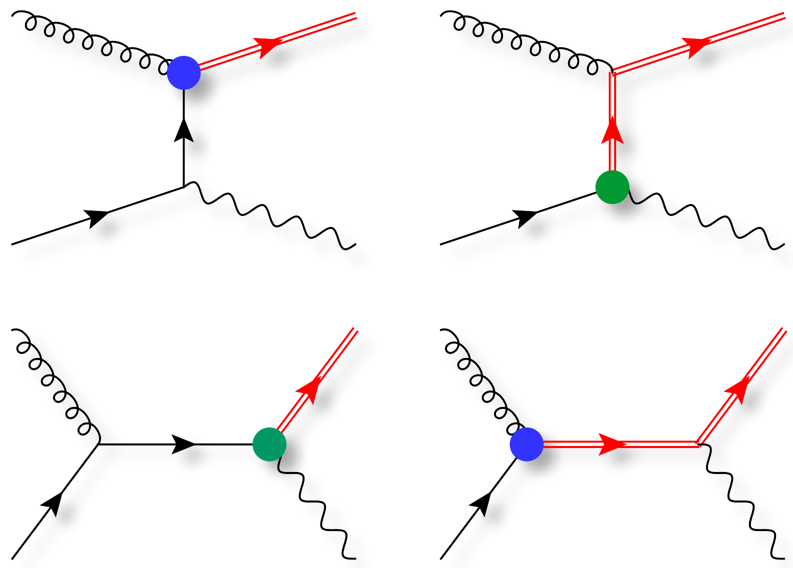
Flavor-conserving

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	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	X		X	X				X		
$pp \to t\tilde{q}$	X		X	X				X		
$pp \to tW$	X		X	X				X	X	X
$pp \to t\bar{t}$	X						X	X	X	X
$pp \to t\bar{t}\gamma$	X	X	X				X	X	X	X
$pp \to t\gamma j$	X	X	X					X		
$pp \to t\bar{t}Z$	X	X	X	X	X	X	X	X	X	X
$pp \to tZj$	X	X	X	X	X	X		X		
$pp \to t\bar{t}h$	X						X	X	X	X
$pp \to t\bar{j}h$	X						X	X		X
$gg \to H, HZ$	X			X	X	X	X			X

Flavor-changing (neutral)

Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to qZ^*, \gamma^* \to ql^+l^-$	X	X	X	X	X	X		X
$t \to q\gamma$				X	X	X		
$t \to qH$						X	X	
$pp \to t$						X		X
$pp \to tZ$	X	X	X	X	X	X		X
$pp \to t\gamma$				X	X	X		X
$pp \to tH$						X	X	X

Top-FCNC operators



available at

http://feynrules.irmp.ucl.ac.be/wiki/TopFCNC

Description of the model & reference

The top effective theory model contains the dimension-six operators affecting top flavor changing processes. The UFO model can be used for computation at the NLO in QCD.

⇨Phys.Rev. D91 (2015) 034024: C. Degrande, F. Maltoni, J. Wang, C. Zhang, *Automatic computations at next-to-leading order in QCD for top-quark flavor-changing neutral processes*

⇨Phys.Rev. D91 (2015) 074017: G. Durieux, F. Maltoni, C. Zhang, *Global approach to top-quark flavor-changing interactions*

Model files

The UFO (TopFCNC.tar.gz) and the FeynRules model (TopEFTFCNC.fr) are available

- Decays and FCNC direct t production is available analytically.
  [1404.1264 CZ], [1305.7386 F. Maltoni, CZ], [hep-ph/0508016 J.J.Liu et al.]
- FCNC associated productions have been implemented.
  [1412.5594 Degrande, Maltoni, Wang, CZ] http://feynrules.irmp.ucl.ac.be/wiki/TopFCNC

Flavor-conserving

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	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	X		X	X				X		
$pp \to t\tilde{q}$	X		X	X				X		
$pp \to tW$	X		X	X				X	X	X
$pp \to t\bar{t}$	X						X	X	X	X
$pp \to t\bar{t}\gamma$	X	X	X				X	X	X	X
$pp \to t\gamma j$	X	X	X					X		
$pp \to t\bar{t}Z$	X	X	X	X	X	X	X	X	X	X
$pp \to tZj$	X	X	X	X	X	X		X		
$pp \to t\bar{t}h$	X						X	X	X	X
$pp \to t\bar{j}h$	X						X	X		X
$gg \to H, HZ$	X			X	X	X	X			X

Flavor-changing (neutral)

Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to qZ^*, \gamma^* \to ql^+l^-$	X	X	X	X	X	X		X
$t \to q\gamma$				X	X	X		
$t \to qH$						X	X	
$pp \to t$						X		X
$pp \to tZ$	X	X	X	X	X	X		X
$pp \to t\gamma$				X	X	X		X
$pp \to tH$						X	X	X

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Flavor-conserving

Process	O_{tG}	O_{tB}	O_{tW}	$O^{(3)}_{\varphi Q}$	$O^{(1)}_{\varphi Q}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	X		X	X				X		
$pp \to t\tilde{q}$	X		X	X				X		
$pp \to tW$	X		X	X				X	X	X
$pp \to t\bar{t}$	X						X	X	X	X
$pp \to t\bar{t}\gamma$	X	X	X				X	X	X	X
$pp \to t\gamma j$	X	X	X					X		
$pp \to t\bar{t}Z$	X	X	X	X	X	X	X	X	X	X
$pp \to tZj$	X	X	X	X	X	X		X		
$pp \to t\bar{t}h$	X						X	X	X	X
$pp \to t\bar{j}h$	X						X	X		X
$gg \to H, HZ$	X			X	X	X	X			X

Flavor-changing (neutral)

Process	$O^{(3)}_{\phi q}$	$O^{(1)}_{\phi q}$	$O^{(1)}_{\phi u}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to qZ^*, \gamma^* \to ql^+l^-$	X	X	X	X	X	X		X
$t \to q\gamma$				X	X	X		
$t \to qH$						X	X	
$pp \to t$						X		X
$pp \to tZ$	X	X	X	X	X	X		X
$pp \to t\gamma$				X	X	X		X
$pp \to tH$						X	X	X

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  [1503.08841 D.B. Franzosi, CZ]

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Flavor-conserving

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	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	X		X	X				X		
$pp \to t\tilde{q}$	X		X	X				X		
$pp \to tW$	X		X	X				X	X	X
$pp \to t\bar{t}$	X						X	X	X	X
$pp \to t\bar{t}\gamma$	X	X	X				X	X	X	X
$pp \to t\gamma j$	X	X	X					X		
$pp \to t\bar{t}Z$	X	X	X	X	X	X	X	X	X	X
$pp \to tZj$	X	X	X	X	X	X		X		
$pp \to t\bar{t}h$	X						X	X	X	X
$pp \to t\bar{j}h$	X						X	X		X
$gg \to H, HZ$	X			X	X	X	X			X

Flavor-changing (neutral)

Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to qZ^*, \gamma^* \to ql^+l^-$	X	X	X	X	X	X		X
$t \to q\gamma$				X	X	X		
$t \to qH$						X	X	
$pp \to t$						X		X
$pp \to tZ$	X	X	X	X	X	X		X
$pp \to t\gamma$				X	X	X		X
$pp \to tH$						X	X	X

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Top-EW operators

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

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

- tbW
  - V/A

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

  - Weak dipole

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

- ttZ
  - V/A

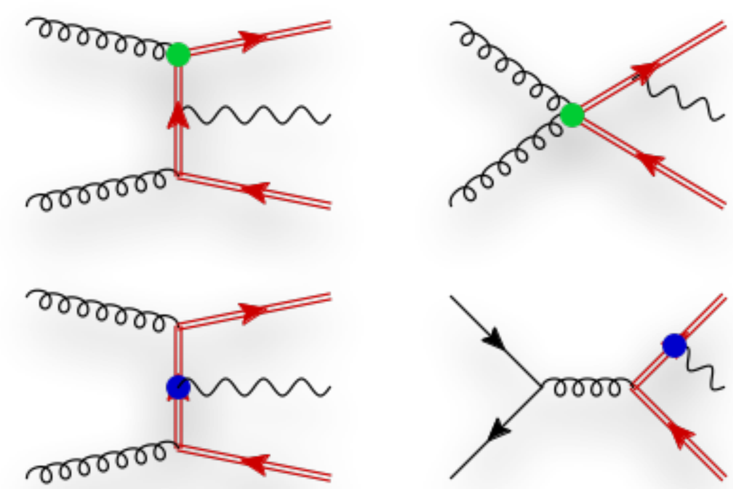
$$O^{(1)}_{\varphi Q} = i(\varphi^\dagger D_\mu \varphi)(\bar{Q}\gamma^\mu Q) \qquad O_{\varphi u} = i(\varphi^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu t)$$

  - Weak dipole O_{tW}

O_{tG}, O_{tW}, O_{tB} mixing

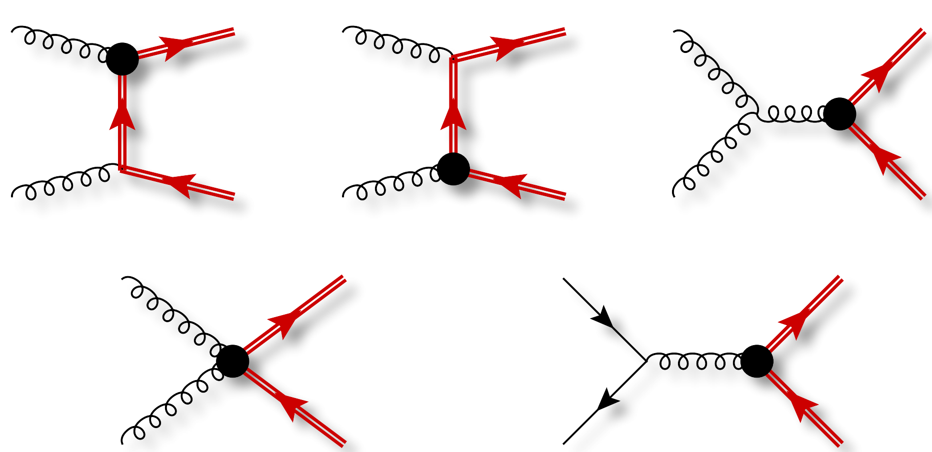
$$\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} \end{pmatrix}$$

ttbar+V

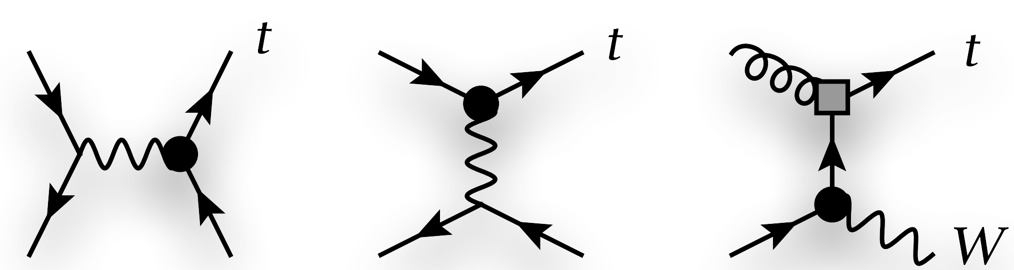


cf. [1404.1005, 1501.0593 Rontsch and Schulze]

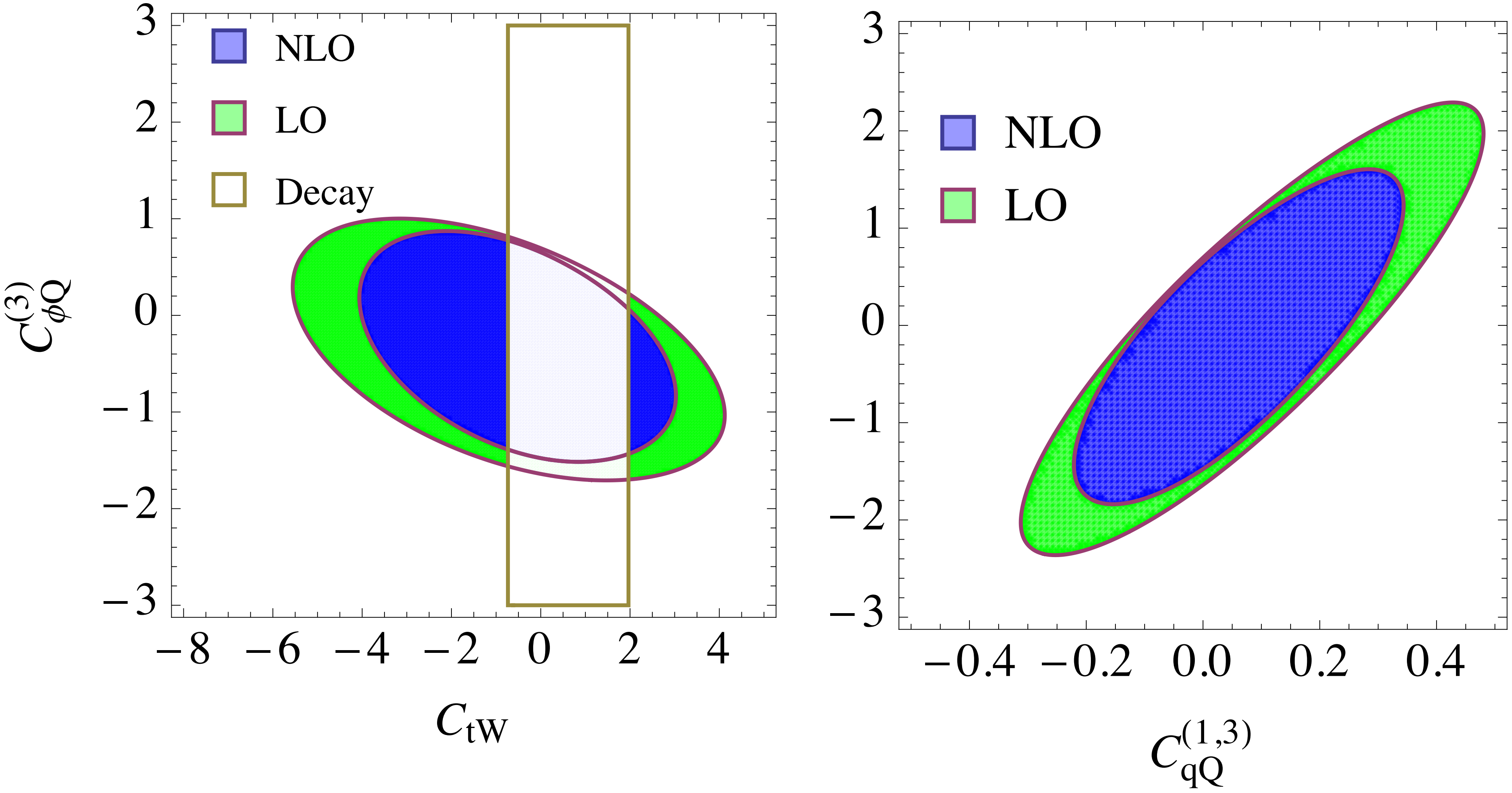
ttbar



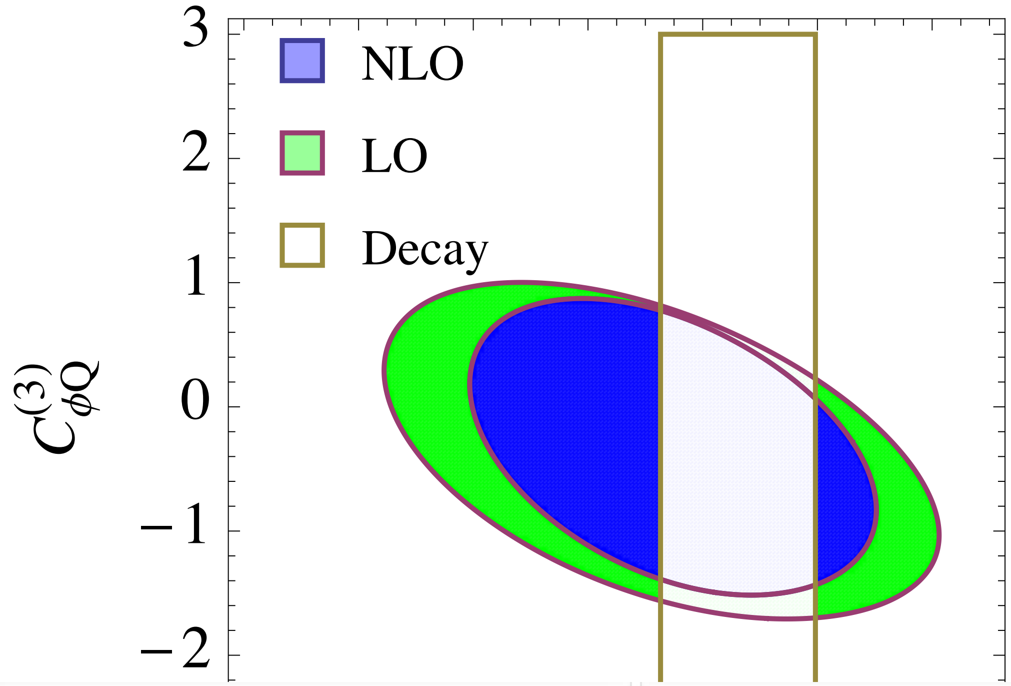
single top

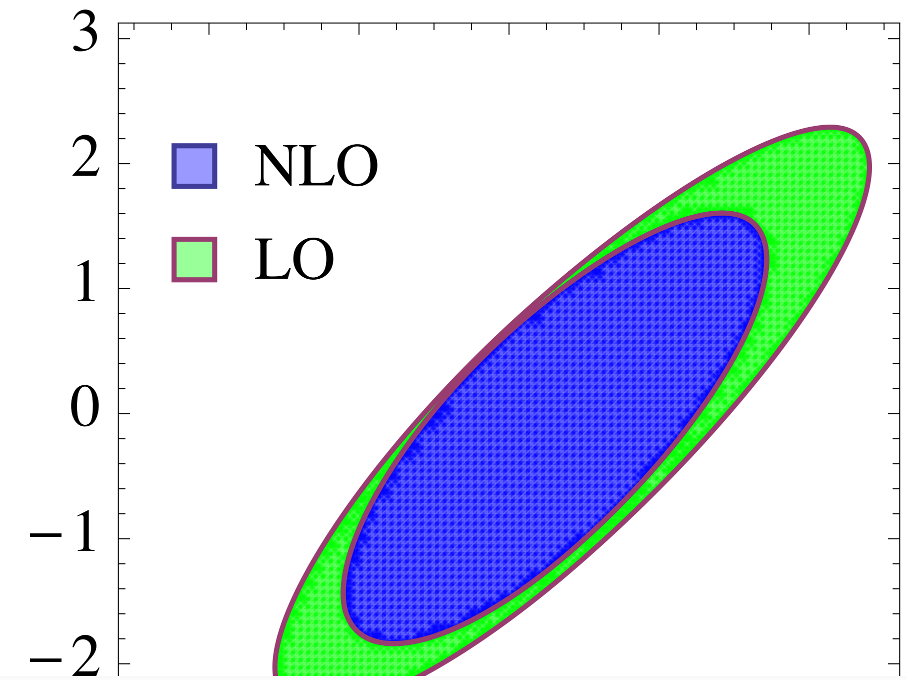


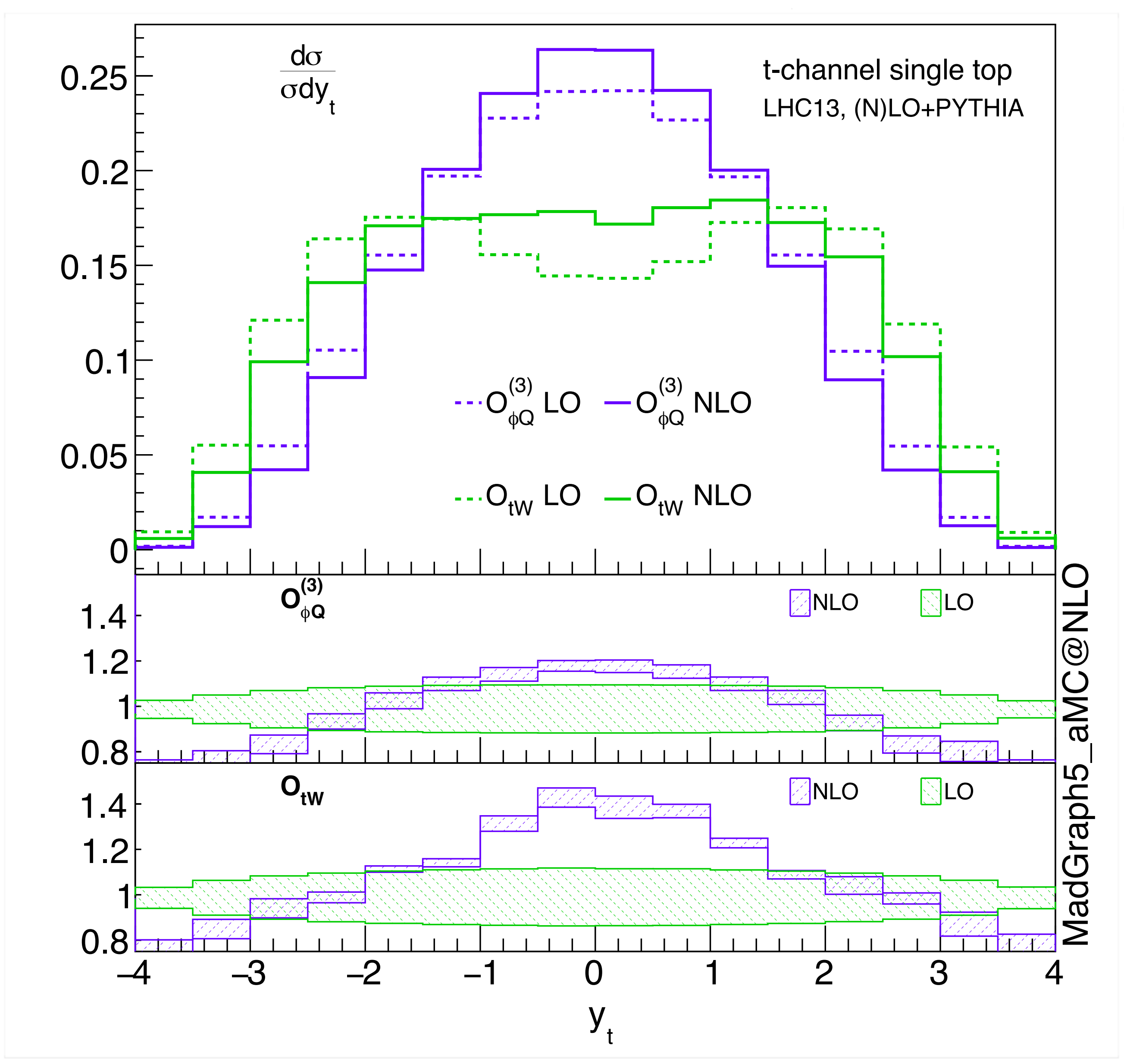
- Operator fit with NLO xsecs: improved limits

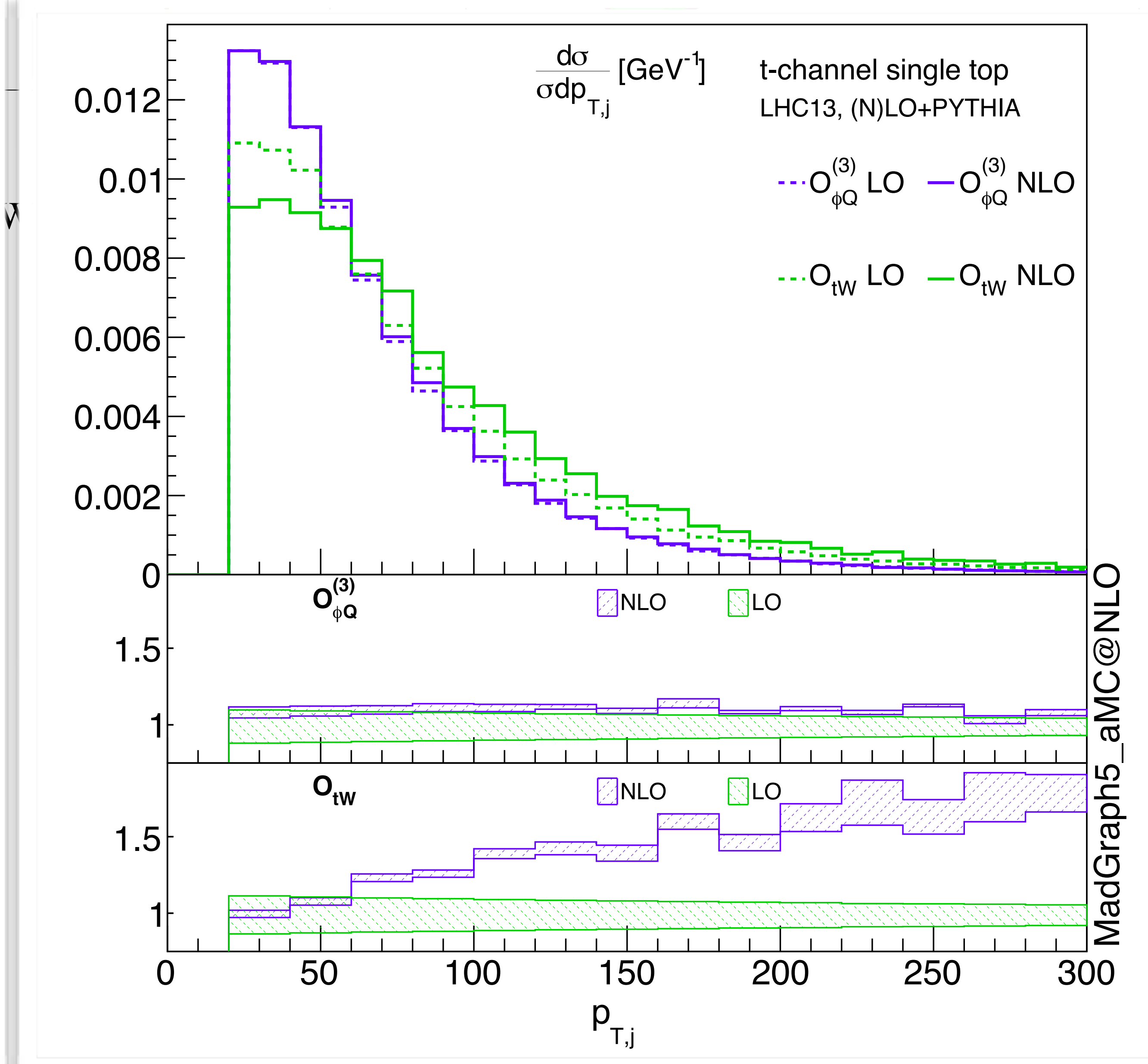


- Operator fit with NLO xsecs: improved limits
- Corrections on on distributions can be important









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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	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	X		X	X				X		
$pp \to t\tilde{q}$	X		X	X				X		
$pp \to tW$	X		X	X				X	X	X
$pp \to t\bar{t}$	X						X	X	X	X
$pp \to t\bar{t}\gamma$	X	X	X				X	X	X	X
$pp \to t\gamma j$	X	X	X					X		
$pp \to t\bar{t}Z$	X	X	X	X	X	X	X	X	X	X
$pp \to tZj$	X	X	X	X	X	X		X		
$pp \to t\bar{t}h$	X						X	X	X	X
$pp \to tjh$	X						X	X		X
$gg \to H, HZ$	X			X	X	X	X			X

Flavor-changing (neutral)

Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to qZ^*, \gamma^* \to ql^+l^-$	X	X	X	X	X	X		X
$t \to q\gamma$				X	X	X		
$t \to qH$						X	X	
$pp \to t$						X		X
$pp \to tZ$	X	X	X	X	X	X		X
$pp \to t\gamma$				X	X	X		X
$pp \to tH$						X	X	X

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$t \to bW \to bl^+\nu$	X		X	X				X		
$pp \to t\tilde{q}$	X		X	X				X		
$pp \to tW$	X		X	X				X	X	X
$pp \to t\bar{t}$	X						X	X	X	X
$pp \to t\bar{t}\gamma$	X	X	X				X	X	X	X
$pp \to t\gamma j$	X	X	X					X		
$pp \to t\bar{t}Z$	X	X	X	X	X	X	X	X	X	X
$pp \to tZj$	X	X	X	X	X	X		X		
$pp \to t\bar{t}h$	X						X	X	X	X
$pp \to t\bar{j}h$	X						X	X		X
$gg \to H, HZ$	X			X	X	X	X			X

Flavor-changing (neutral)

Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to qZ^*, \gamma^* \to ql^+l^-$	X	X	X	X	X	X		X
$t \to q\gamma$				X	X	X		
$t \to qH$						X	X	
$pp \to t$						X		X
$pp \to tZ$	X	X	X	X	X	X		X
$pp \to t\gamma$				X	X	X		X
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- ttH and tHj: ongoing

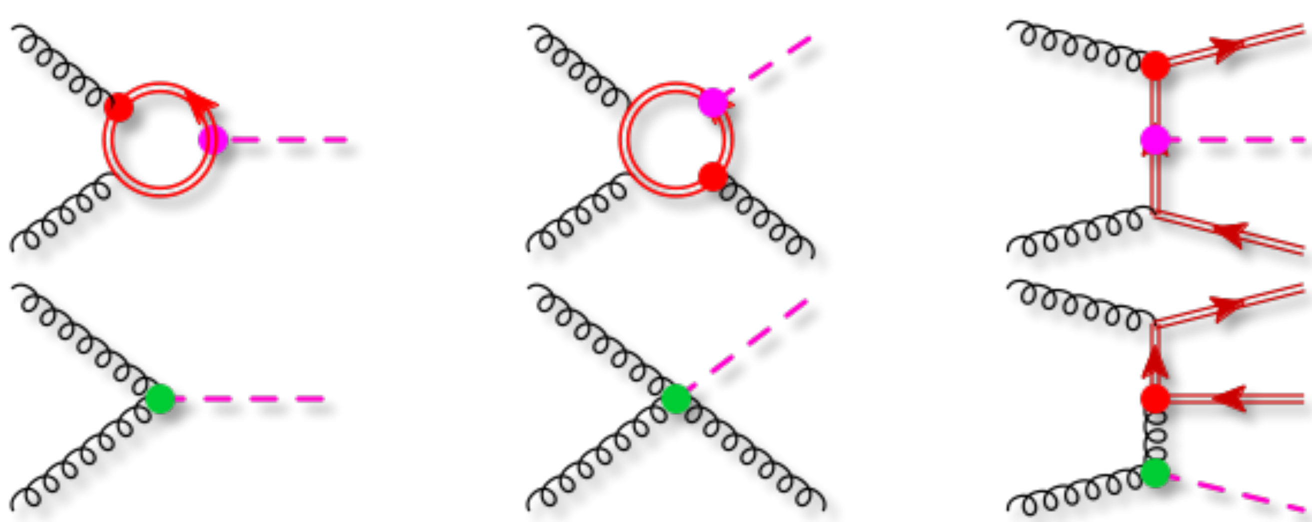
Top-Higgs operators in progress

chromo-dipole $O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi}G_{\mu\nu}$

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

gluon-Higgs $O_{\phi G} = y_t^2 (\phi^\dagger\phi)G^A_{\mu\nu}G^{A\mu\nu}$

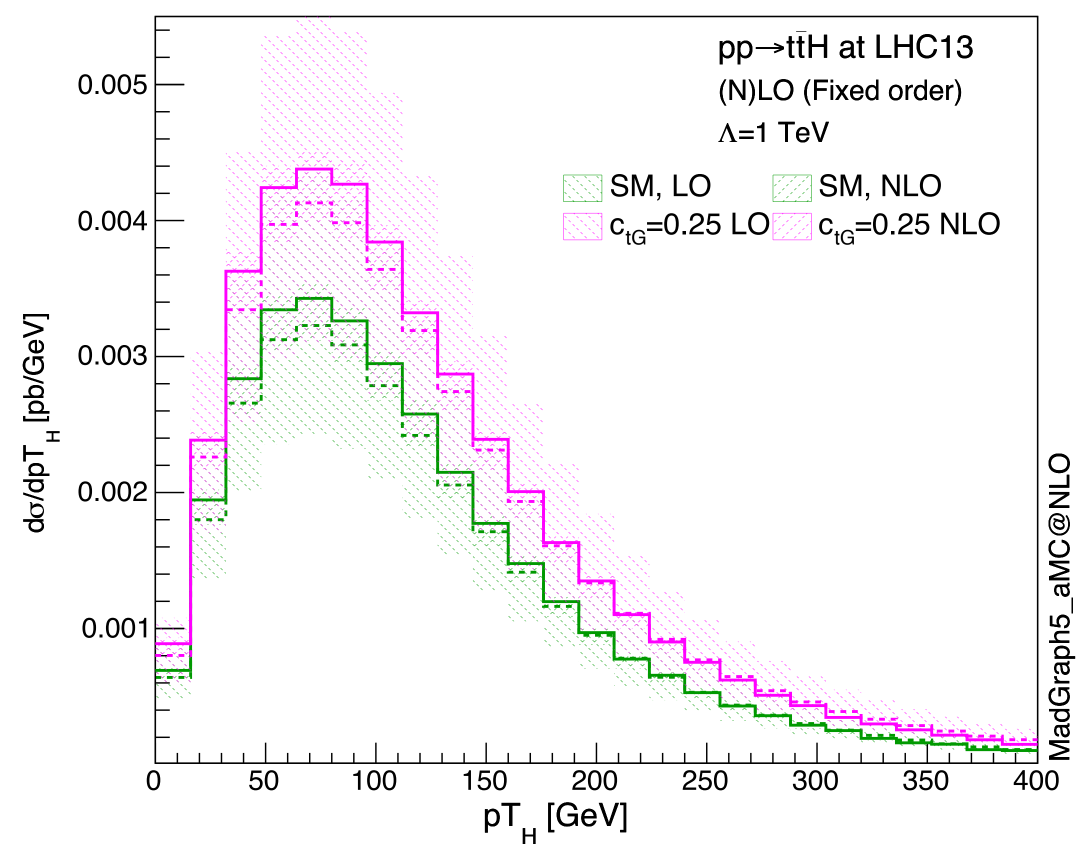
$$\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 \\ 4 & -1 & 4 \\ \frac{1}{4} & 0 & -\frac{7}{4} \end{pmatrix}$$



(very preliminary) ttH at LHC 13 TeV

	O_{tG}	$O_{t\phi}$	$O_{\phi G}$
LO	513^{+188}_{-132}	-60^{+15}_{-22}	690^{+256}_{-178}
NLO	523^{+11}_{-46}	-65^{+7}_{-3}	936^{+131}_{-139}

[in fb]



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Flavor-conserving

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	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	X		X	X				X		
$pp \to t\tilde{q}$	X		X	X				X		
$pp \to tW$	X		X	X				X	X	X
$pp \to t\bar{t}$	X						X	X	X	X
$pp \to t\bar{t}\gamma$	X	X	X				X	X	X	X
$pp \to t\gamma j$	X	X	X					X		
$pp \to t\bar{t}Z$	X	X	X	X	X	X	X	X	X	X
$pp \to tZj$	X	X	X	X	X	X		X		
$pp \to t\bar{t}h$	X						X	X	X	X
$pp \to tjh$	X						X	X		X
$gg \to H, HZ$	X			X	X	X	X			X

Flavor-changing (neutral)

Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to qZ^*, \gamma^* \to ql^+l^-$	X	X	X	X	X	X		X
$t \to q\gamma$				X	X	X		
$t \to qH$						X	X	
$pp \to t$						X		X
$pp \to tZ$	X	X	X	X	X	X		X
$pp \to t\gamma$				X	X	X		X
$pp \to tH$						X	X	X

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Flavor-conserving

Process	O_{tG}	O_{tB}	O_{tW}	$O^{(3)}_{\varphi Q}$	$O^{(1)}_{\varphi Q}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	X		X	X				X		
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$pp \to tW$	X		X	X				X	X	X
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$pp \to t\gamma j$	X	X	X					X		
$pp \to t\bar{t}Z$	X	X	X	X	X	X	X	X	X	X
$pp \to tZj$	X	X	X	X	X	X		X		
$pp \to t\bar{t}h$	X						X	X	X	X
$pp \to t\bar{j}h$	X						X	X		X
$gg \to H, HZ$	X			X	X	X	X			X

Flavor-changing (neutral)

Process	$O^{(3)}_{\phi q}$	$O^{(1)}_{\phi q}$	$O^{(1)}_{\phi u}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to qZ^*, \gamma^* \to ql^+l^-$	X	X	X	X	X	X		X
$t \to q\gamma$				X	X	X		
$t \to qH$						X	X	
$pp \to t$						X		X
$pp \to tZ$	X	X	X	X	X	X		X
$pp \to t\gamma$				X	X	X		X
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- ttH and tHj: ongoing
- Four fermion operators are planned

Summary

- EFT models are available in several MC tools. In particular the UFO interface provides full support for arbitrary effective vertices.

- UFO models are publicly available
  https://feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage

- Ongoing developments at NLO with MG5, including Higgs characterisation, HEL, top EFT, etc., and eventually full SMEFT@NLO can be expected.

Backups

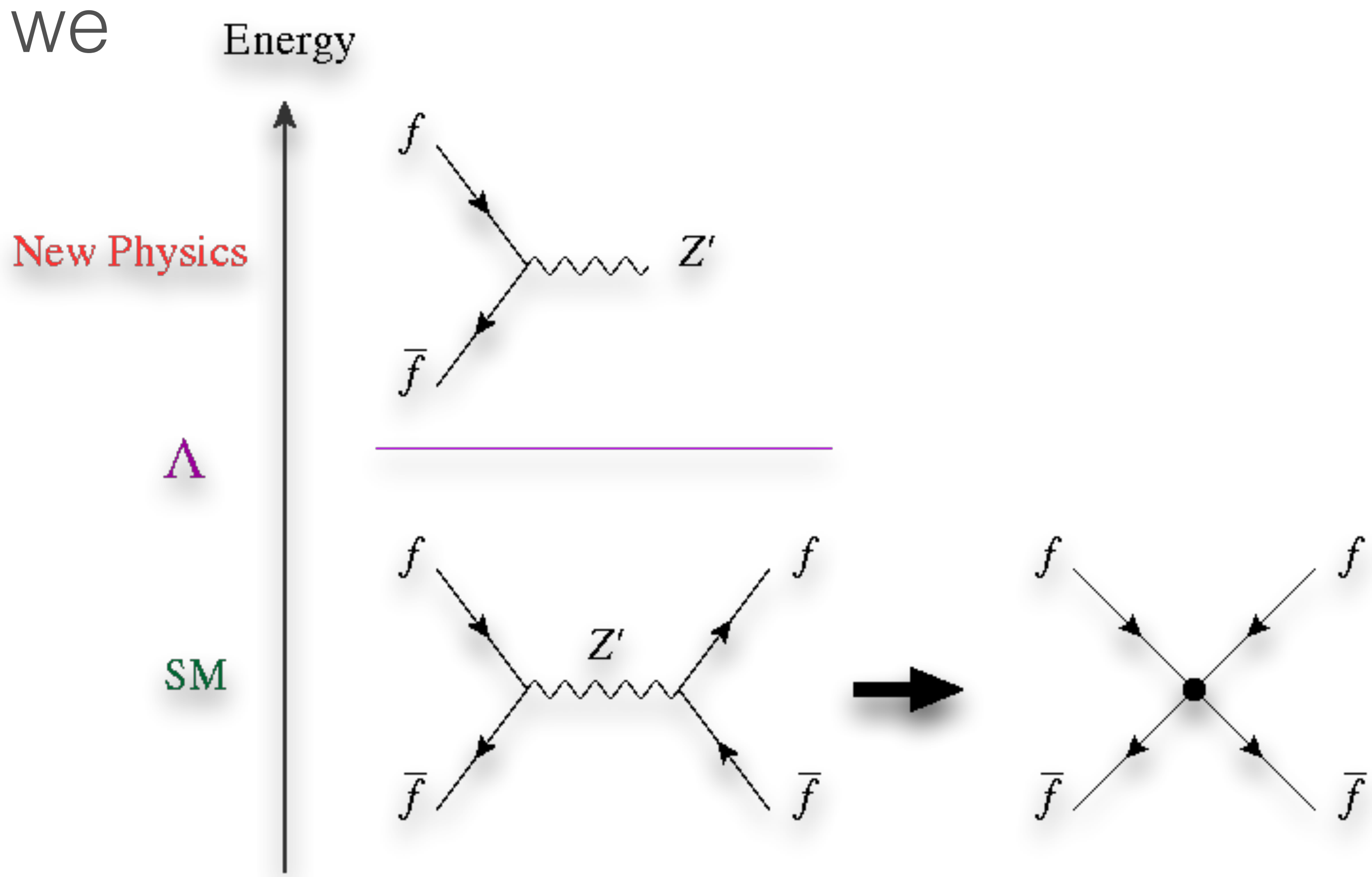
EFT approach to BSM

- Instead of looking for new particles, EFT focus on new interactions (of the SM particles).

- SM is the most general Lagrangian at DIM-4. To look for something new, we go to DIM-6.

- SM Lagrangian supplemented with DIM-6 operators (hence SMEFT)

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



Basis

EW-Higgs operators: a comparison

[S. Willenbrock and CZ 2014]

Warsaw/BW/Standard	HISZ	SILH/GGPR
$\mathcal{O}_W = \epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$\mathcal{O}_{WWW} = \mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}_\rho^\mu]$	$\mathcal{O}_{3W} = \frac{1}{3!} g\epsilon_{abc} W_\mu^{a\nu} W_{\nu\rho}^b W^{c\rho\mu}$
$\mathcal{O}_{\varphi W} = \varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$	—
$\mathcal{O}_{\varphi B} = \varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi$	$\mathcal{O}_{BB} = g'^2 \|H\|^2 B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{\varphi WB} = \varphi^\dagger \sigma^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$	—
—	$\mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi)$	$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W_{\mu\nu}^a$
—	$\mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$	$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$
—	$\mathcal{O}_{DW} = \mathrm{Tr}\left([D_\mu, \hat{W}_{\nu\rho}][D^\mu, \hat{W}^{\nu\rho}]\right)$	$\mathcal{O}_{2W} = -\frac{1}{2}\left(D^\mu W_{\mu\nu}^a\right)^2$
—	$\mathcal{O}_{DB} = -\frac{g'^2}{2}(\partial_\mu B_{\nu\rho})(\partial^\mu B^{\nu\rho})$	$\mathcal{O}_{2B} = -\frac{1}{2}\left(\partial^\mu B_{\mu\nu}\right)^2$
—	—	$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W_{\mu\nu}^a$
—	—	$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_{\varphi D} = \left(\varphi^\dagger D^\mu \varphi\right)^* \left(\varphi^\dagger D_\mu \varphi\right)$	$\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \Phi \Phi^\dagger (D^\mu \Phi)$	$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
$\mathcal{O}_{\varphi\Box} = (\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$\mathcal{O}_{\Phi,2} = \frac{1}{2}\partial_\mu(\Phi^\dagger \Phi)\partial^\mu(\Phi^\dagger \Phi)$	$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \|H\|^2)^2$
$\mathcal{O}_\varphi = (\varphi^\dagger \varphi)^3$	$\mathcal{O}_{\Phi,3} = \frac{1}{3}\left(\Phi^\dagger \Phi\right)^3$	$\mathcal{O}_6 = \lambda \|H\|^6$
—	$\mathcal{O}_{\Phi,4} = (D_\mu \Phi)^\dagger (D^\mu \Phi)(\Phi^\dagger \Phi)$	—

- EOM can be applied in both directions

$$c_B\mathcal{O}_B \quad \leftrightarrow \quad c_B\frac{g'^2}{g_*^2}\left[-\frac{1}{2}\mathcal{O}_T+\frac{1}{2}\sum_f\left(Y_L^f\mathcal{O}_L^f+Y_R^f\mathcal{O}_R^f\right)\right] ,$$

$$c_W\mathcal{O}_W \quad \leftrightarrow \quad c_W\frac{g^2}{g_*^2}\left[-\frac{3}{2}\mathcal{O}_H+2\mathcal{O}_6+\frac{1}{2}(\mathcal{O}_{y_u}+\mathcal{O}_{y_d}+\mathcal{O}_{y_e}+\text{h.c.})+\frac{1}{4}\sum_f\mathcal{O}_L^{(3)\,f}\right]$$

- Warsaw/BW basis: Bosonic->Fermionic
  - Universal for 3 generations. **Convenient for RG**.
- HISZ, SILH, EGGM: Fermionic->Bosonic: Eliminiate
  - **Convenient for PEWM, TGC, and Higgs**
    - 2 flat directions in PEWM become more transparent
    - 3 TGC couplings directly related to 3 operators

- EOM can be applied in both directions

Gauge boson+Higgs

$$c_B\mathcal{O}_B \leftrightarrow c_B\frac{g'^2}{g_*^2}\left[-\frac{1}{2}\mathcal{O}_T+\frac{1}{2}\sum_f\left(Y_L^f\mathcal{O}_L^f+Y_R^f\mathcal{O}_R^f\right)\right],$$
$$c_W\mathcal{O}_W \leftrightarrow c_W\frac{g^2}{g_*^2}\left[-\frac{3}{2}\mathcal{O}_H+2\mathcal{O}_6+\frac{1}{2}(\mathcal{O}_{y_u}+\mathcal{O}_{y_d}+\mathcal{O}_{y_e}+\text{h.c.})+\frac{1}{4}\sum_f\mathcal{O}_L^{(3)\,f}\right]$$

with Fermions, summed over 3 generations

- Warsaw/BW basis: Bosonic->Fermionic
  - Universal for 3 generations. **Convenient for RG**.
- HISZ, SILH, EGGM: Fermionic->Bosonic: Eliminiate

$$(H^\dagger\tau^a\overset{\leftrightarrow}{D}^\mu H)(\bar{L}_1\gamma_\mu\tau^a L_1)$$
$$(H^\dagger\overset{\leftrightarrow}{D}^\mu H)(\bar{e}\gamma_\mu e)$$
$$(\bar{u}\gamma^\mu t_s^A u)(\bar{d}\gamma_\mu t_s^A d)$$
$$(\bar{L}_1\gamma^\mu\tau^a L_1)(\bar{L}_1\gamma_\mu\tau^a L_1)$$
$$(\bar{e}\gamma^\mu e)(\bar{e}\gamma_\mu e)$$

  - **Convenient for PEWM, TGC, and Higgs**
    - 2 flat directions in PEWM become more transparent
    - 3 TGC couplings directly related to 3 operators

[A. Falkowski and F. Riva 2014]

[C. Grojean et al. 2006]

- **2 flat directions** in PEWM in Warsaw/BW
  - Z-pole data involve 10 operators
  - However, only 8 are really constrained.
    - Thus 2 directions are weakly constrained
    - e.g., when marginalizing over other operators,

      i.e. a factor of ~2500 weaker.
    - Becomes ~10 in one of the “bosonic” bases.

- **2 flat directions** in PEWM in Warsaw/BW
  - Z-pole data involve 10 operators

$$O_{\phi l},\ O^{(3)}_{\phi l},\ O_{\phi e},\ O_{\phi Q},\ O^{(3)}_{\phi Q},\ O_{\phi u},\ O_{\phi d},\ O_{ll},\ O_{WB},\ O^{(3)}_{\phi}$$

  - However, only 8 are really constrained. [A. Falkowski and F. Riva 2014]
    - Thus 2 directions are weakly constrained [C. Grojean et al. 2006]

$$\begin{aligned} -\frac{2gscv^2}{\alpha}O_S - \frac{g'v^2}{\alpha}O_T + g'O^Y_{hf} &= 2iB_{\mu\nu}D^\mu h^\dagger D^\nu h, \\ -\frac{4g'scv^2}{\alpha}O_S + g(O^t_{hl} + O^t_{hq}) &= 4iW^a_{\mu\nu}D^\mu h^\dagger \sigma^a D^\nu h. \end{aligned}$$

    - e.g., when marginalizing over other operators,

$$S = 0.05 \pm 0.10,\ \ T = -0.04 \pm 0.10 \quad \Rightarrow \quad S = 53 \pm 250,\ \ T = 36 \pm 223$$

i.e. a factor of ~2500 weaker.

[B. Grinstein et al. 2013]

- Becomes ~10 in one of the “bosonic” bases.

$$O_{\phi l},\ O_{\phi l}^{(3)},\ O_{\phi e},\ O_{\phi Q},\ O_{\phi Q}^{(3)},\ O_{\phi u},\ O_{\phi d},\ O_{ll},\ O_{WB},\ O_{\phi}^{(3)}$$

It is incorrect ignore all these operators, just because they are constrained by precision EW tests.

$$O_{\phi l},\ O_{\phi l}^{(3)},\ O_{\phi e},\ O_{\phi Q},\ O_{\phi Q}^{(3)},\ O_{\phi u},\ O_{\phi d},\ O_{ll},\ O_{WB},\ O_{\phi}^{(3)}$$

↑

It is incorrect ignore all these operators, just because they are constrained by precision EW tests.

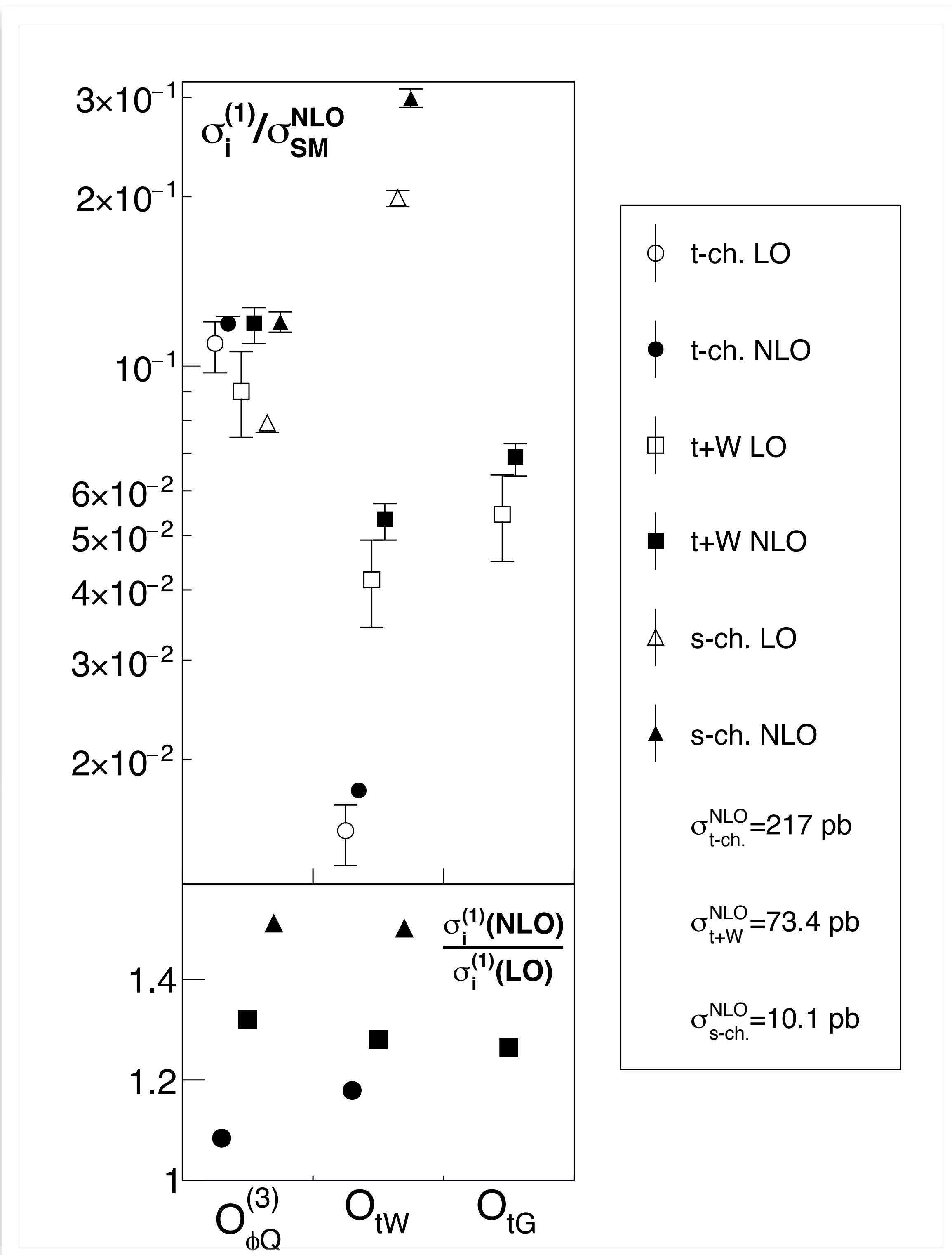
- **TGC** also look more transparent in SILH/HISZ bases
    - Traditionally uses $g_1^Z,\ \kappa_\gamma,\ \lambda_Z$
    - In **Warsaw/BW** basis, only O_{BW} and O_{3W} enters directly. Remaining degree of freedom comes from shifting input parameters.
    - In **SILH** basis, TGC are directly given by

$$O_{HW} + O_{HB},\ O_W - O_B + O_{HW} - O_{HB},\ O_{3W}$$

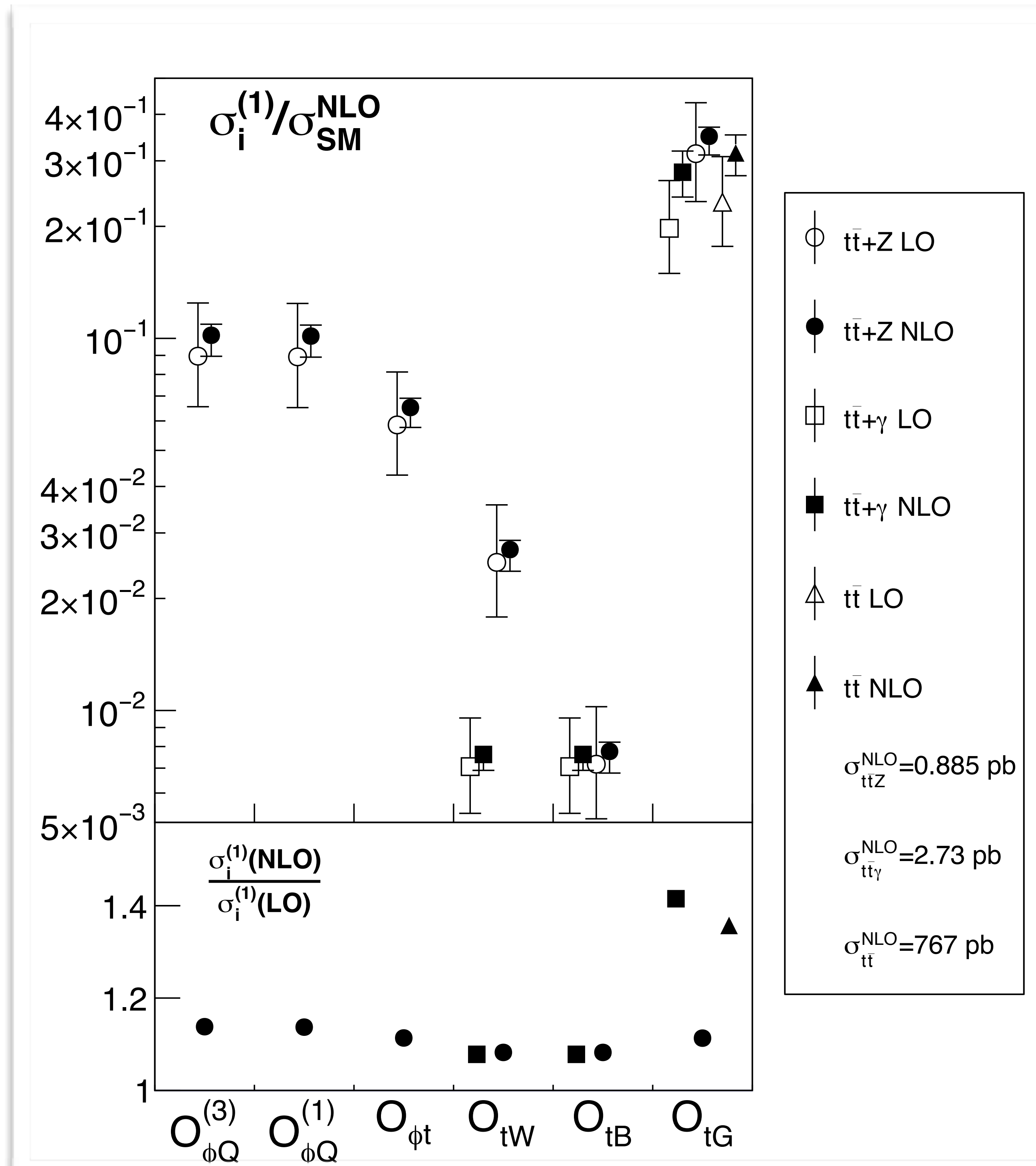
Cross sections at LHC 13

$$\sigma = \sigma_{\rm SM} + C_i \frac{\rm TeV^2}{\Lambda^2}\sigma_i^{(1)} + \mathcal{O}(\Lambda^{-4})$$

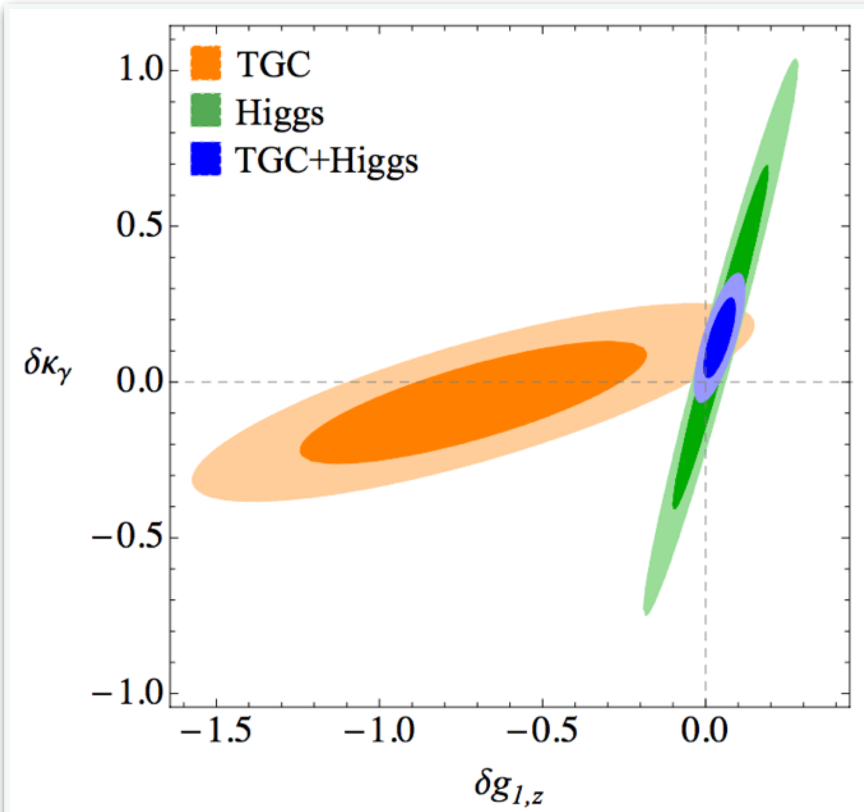
single top



ttbar+V

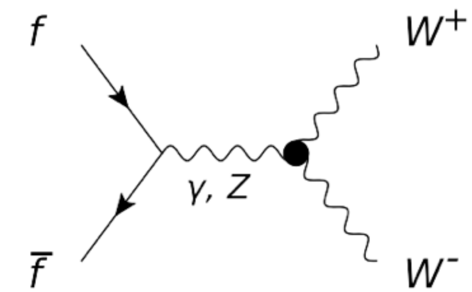


TGC fit, with W-pair production, plus Higgs data



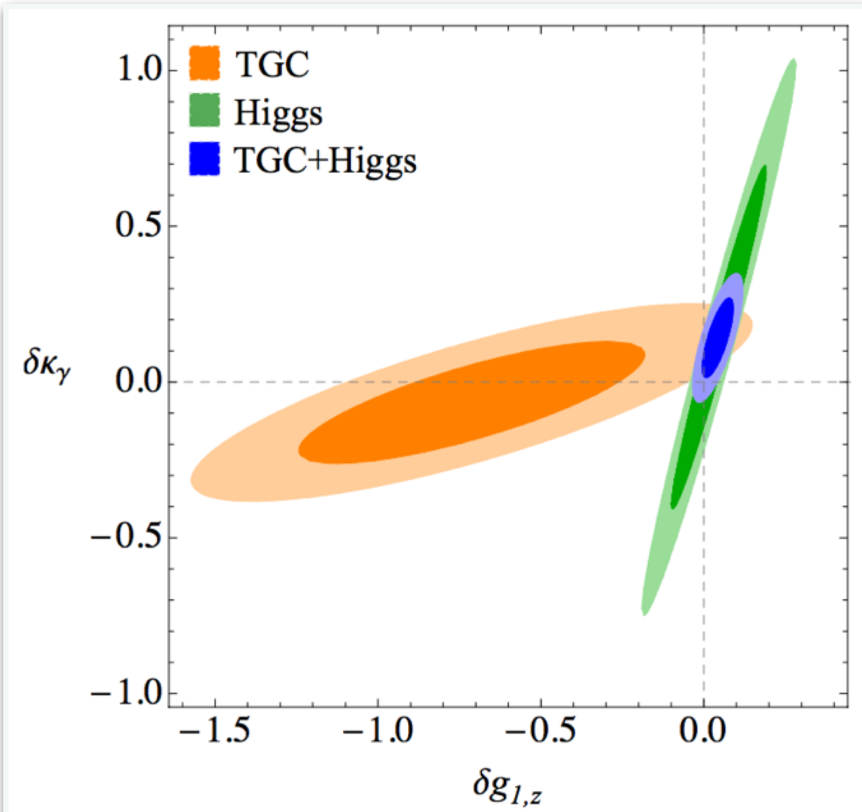
[A. Falkowski et al. 2015]

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho^\mu]$$
$$\mathcal{O}_W = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_B = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi),$$



Higgs is the new tool
to precision EW physics

TGC fit, with W-pair production, plus Higgs data



[A. Falkowski et al. 2015]

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho^\mu]$$
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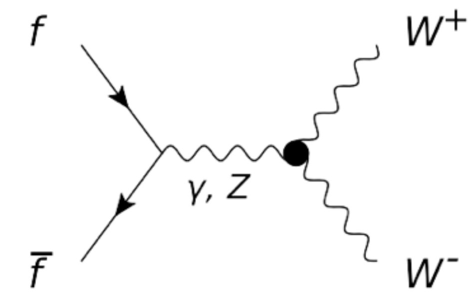
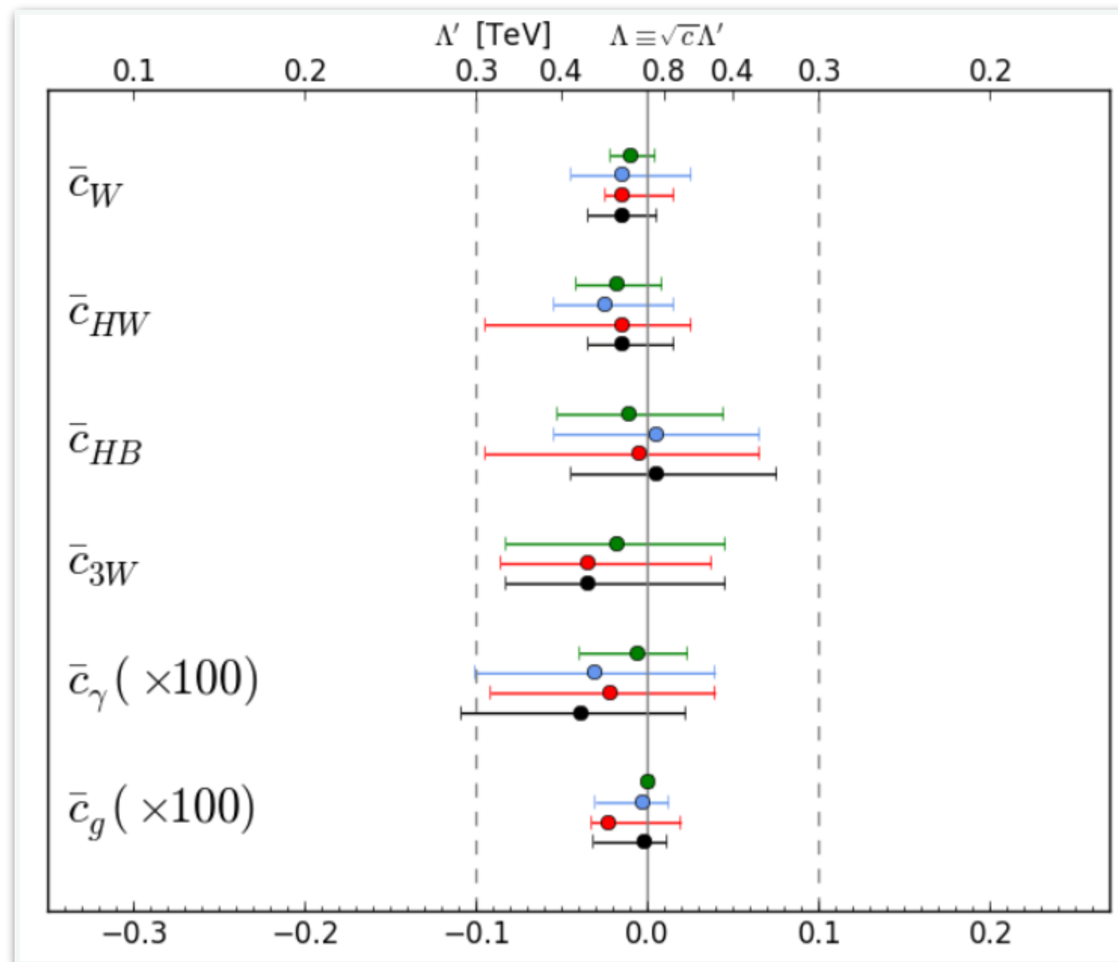


Higgs is the new tool
to precision EW physics

Combined fit for Higgs op.

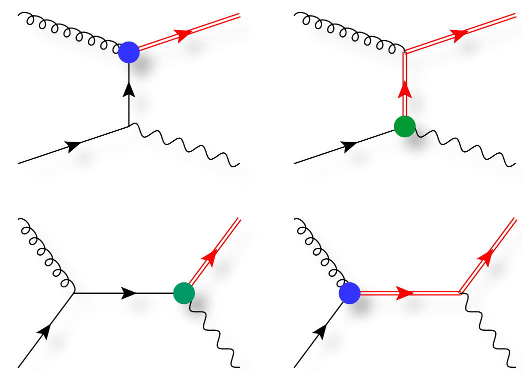
[J. Ellis et al. 2014]

Signal-strength data
combined with TGC
(Higgs, TGC, combination)

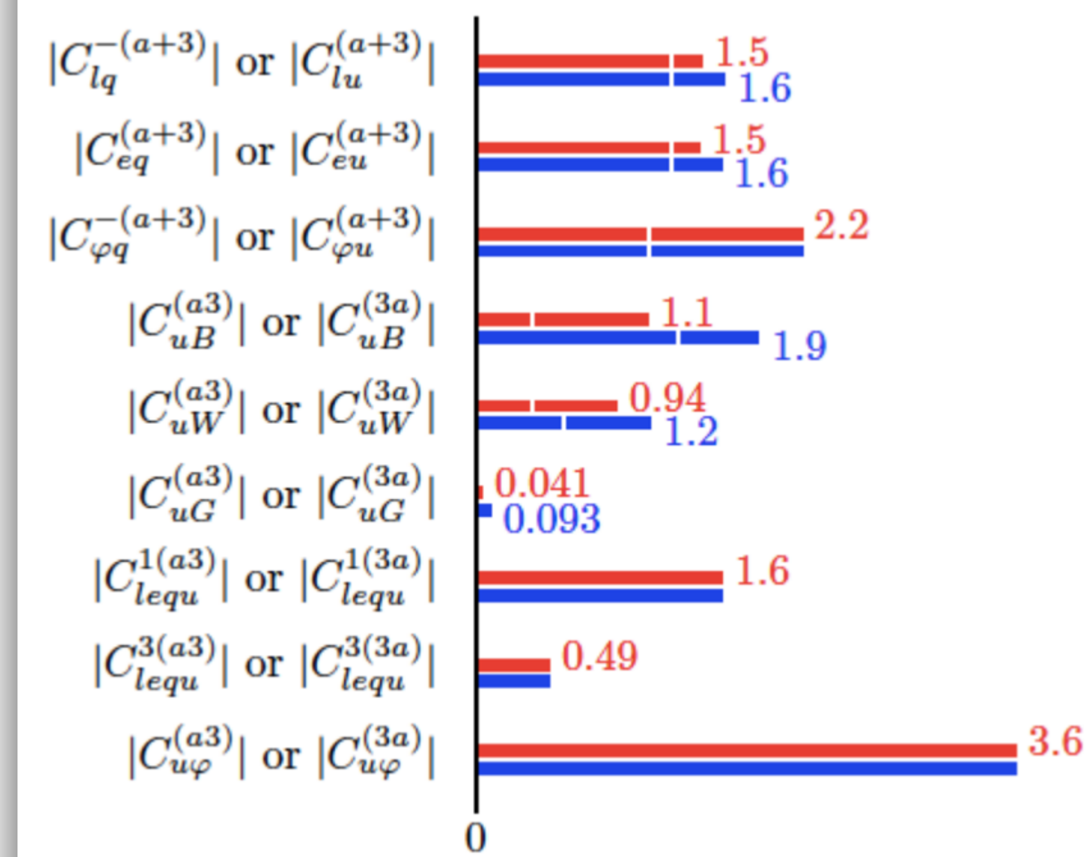


See also [A. Falkowski, F. Riva 2014] [A. Pomarol, F. Riva 2013] [T. Corbett et al. 2015] [T. Corbett et al. 2013] [H. Belusca-Maito 2014] and many others…

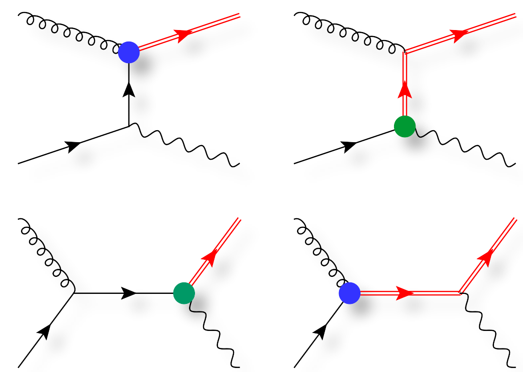
- Top fit: FCNC (at NLO)



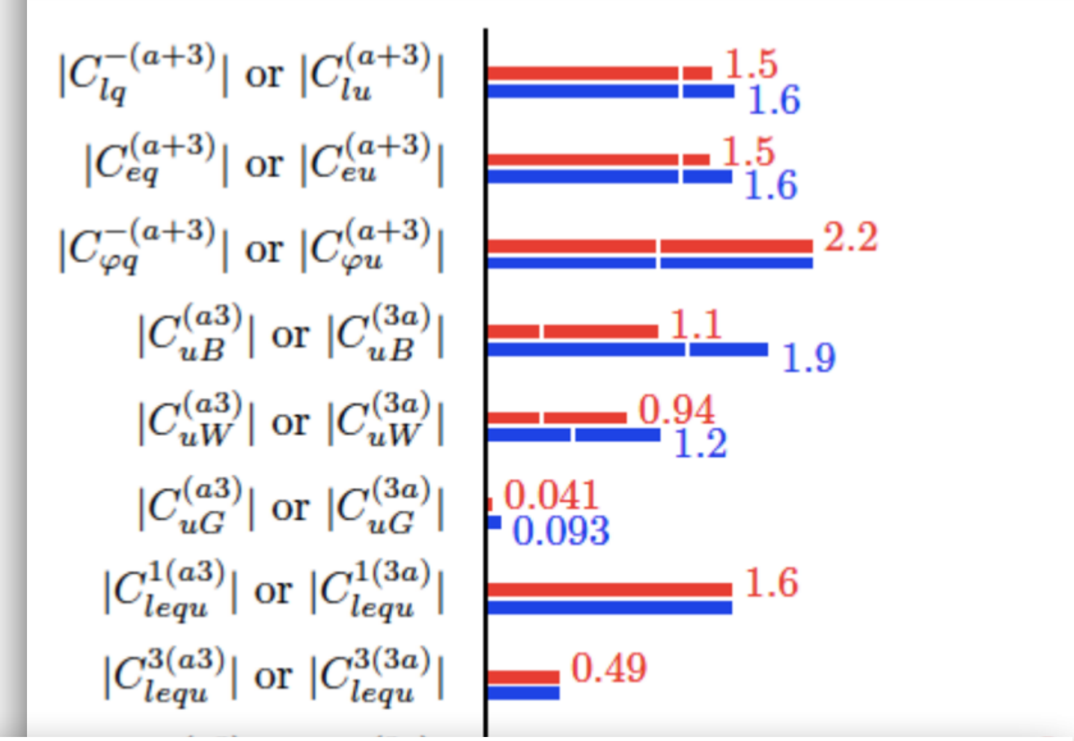
[1412.7166 Durieux, Maltoni, CZ]

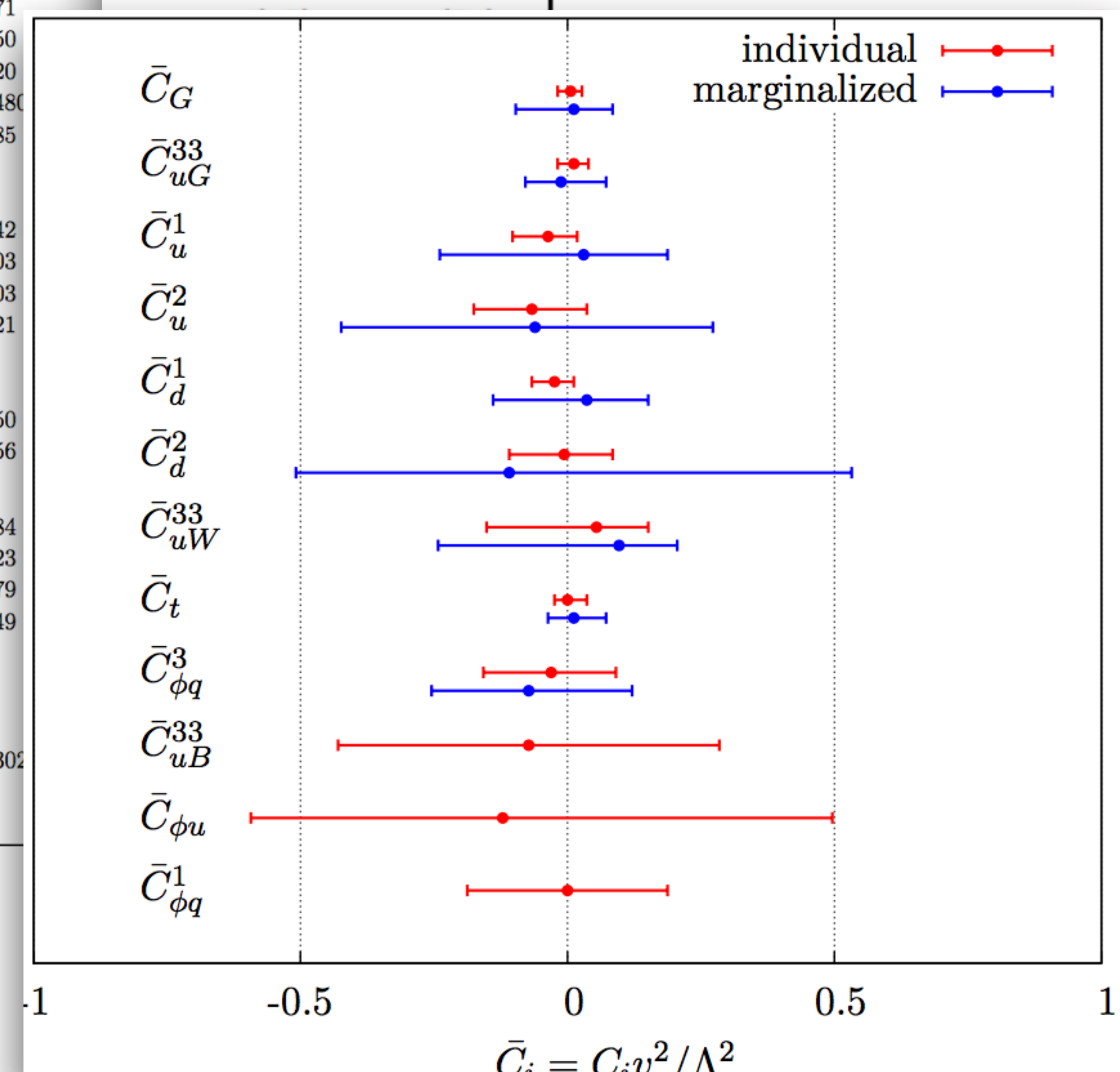


- Top fit: FCNC (at NLO)
- Top fit: flavor conserving



[1412.7166 Durieux, Maltoni, CZ]





Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.	Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.
Top pair production							
Total cross-sections:				Differential cross-sections:			
ATLAS	7	lepton+jets	1406.5375	ATLAS	7	$p_T(t), M_{t\bar t}, \vert y_{t\bar t}\vert$	1407.0371
ATLAS	7	dilepton	1202.4892	CDF	1.96	$M_{t\bar t}$	0903.2850
ATLAS	7	lepton+tau	1205.3067	CMS	7	$p_T(t), M_{t\bar t}, y_t, y_{t\bar t}$	1211.2220
ATLAS	7	lepton w/o b jets	1201.1889	CMS	8	$p_T(t), M_{t\bar t}, y_t, y_{t\bar t}$	1505.0448
ATLAS	7	lepton w/ b jets	1406.5375	DØ	1.96	$M_{t\bar t}, p_T(t), \vert y_t\vert$	1401.5785
ATLAS	7	tau+jets	1211.7205				
ATLAS	7	$t\bar t, Z\gamma, WW$	1407.0573	Charge asymmetries:			
ATLAS	8	dilepton	1202.4892	ATLAS	7	A_C (inclusive+$M_{t\bar t}, y_{t\bar t}$)	1311.6742
CMS	7	all hadronic	1302.0508	CMS	7	A_C (inclusive+$M_{t\bar t}, y_{t\bar t}$)	1402.3803
CMS	7	dilepton	1208.2761	CDF	1.96	A_{FB} (inclusive+$M_{t\bar t}, y_{t\bar t}$)	1211.1003
CMS	7	lepton+jets	1212.6682	DØ	1.96	A_{FB} (inclusive+$M_{t\bar t}, y_{t\bar t}$)	1405.0421
CMS	7	lepton+tau	1203.6810				
CMS	7	tau+jets	1301.5755	Top widths:			
CMS	8	dilepton	1312.7582	DØ	1.96	Γ_{top}	1308.4050
CDF + DØ	1.96	Combined world average	1309.7570	CDF	1.96	Γ_{top}	1201.4156
Single top production				*W*-boson helicity fractions:			
ATLAS	7	t-channel (differential)	1406.7844	ATLAS	7		1205.2484
CDF	1.96	s-channel (total)	1402.0484	CDF	1.96		1211.4523
CMS	7	t-channel (total)	1406.7844	CMS	7		1308.3879
CMS	8	t-channel (total)	1406.7844	DØ	1.96		1011.6549
DØ	1.96	s-channel (total)	0907.4259				
DØ	1.96	t-channel (total)	1105.2788				
Associated production				*Run II data*			
ATLAS	7	$t\bar t\gamma$	1502.00586	CMS	13	$t\bar t$ (dilepton)	1510.05302
ATLAS	8	$t\bar t Z$	1509.05276				
CMS	8	$t\bar t Z$	1406.7830				

[1512.03360 A. Buckley, et al.]