EFT in the top sector

Eleni Vryonidou
CERN TH

SM@LHC
Zurich
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SMEFT

New Interactions of SM particles

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

Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653

Grzadkowski et al arxiv:1008.4884

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

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

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

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

Outline

- **Top EFT: recent theory progress**
- Global top EFT fit

Top-quark operators and how to look for them

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

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

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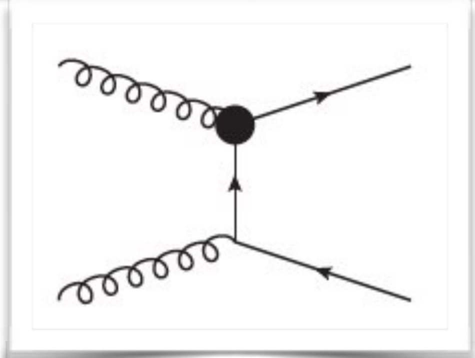
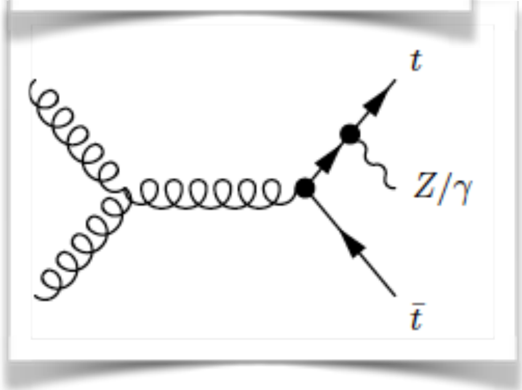
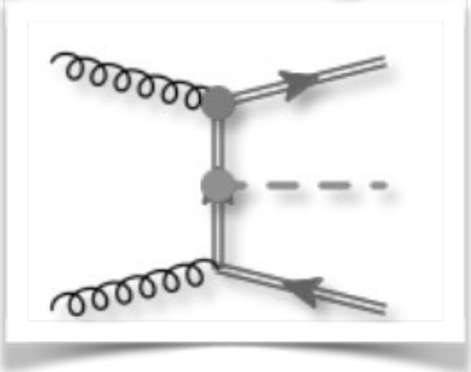
+four-fermion operators

+non-top operators (mixing)







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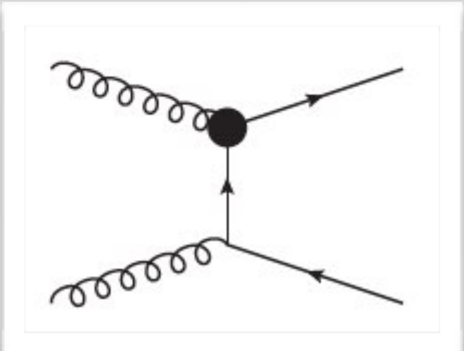

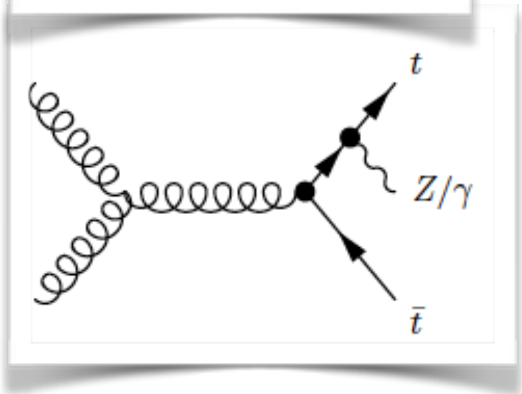

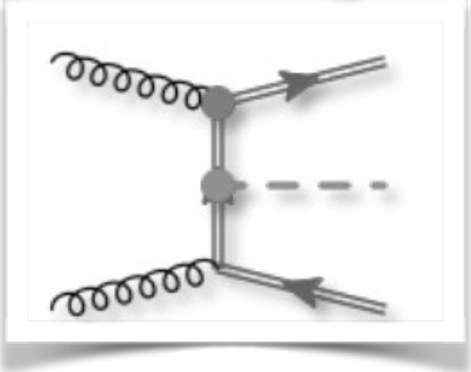

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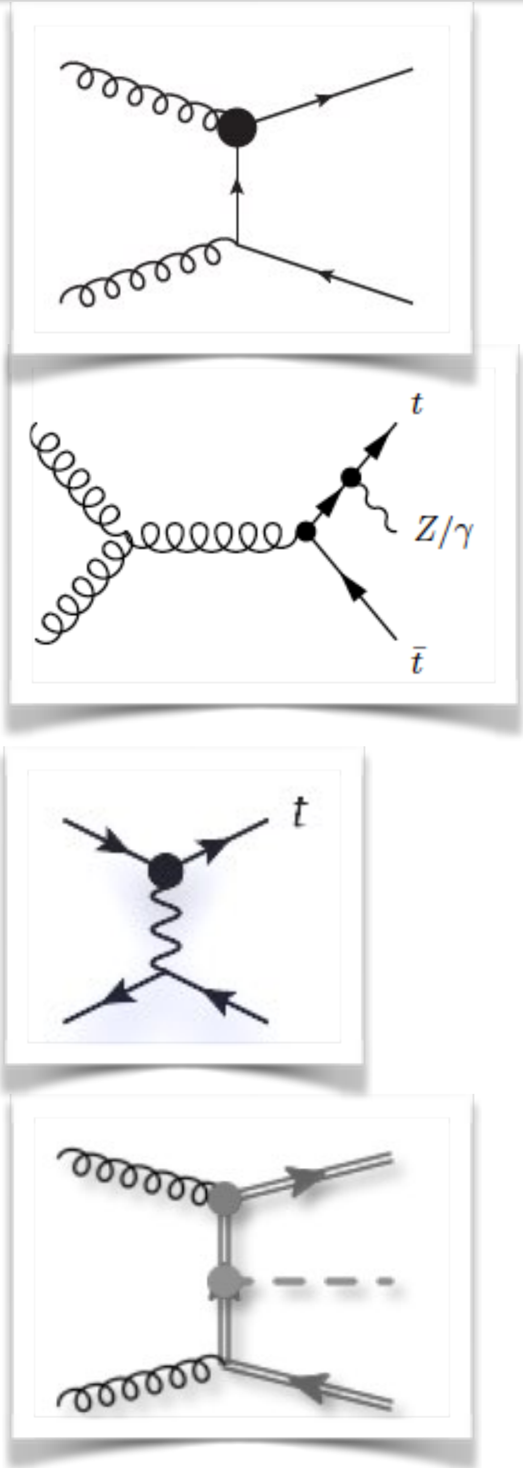

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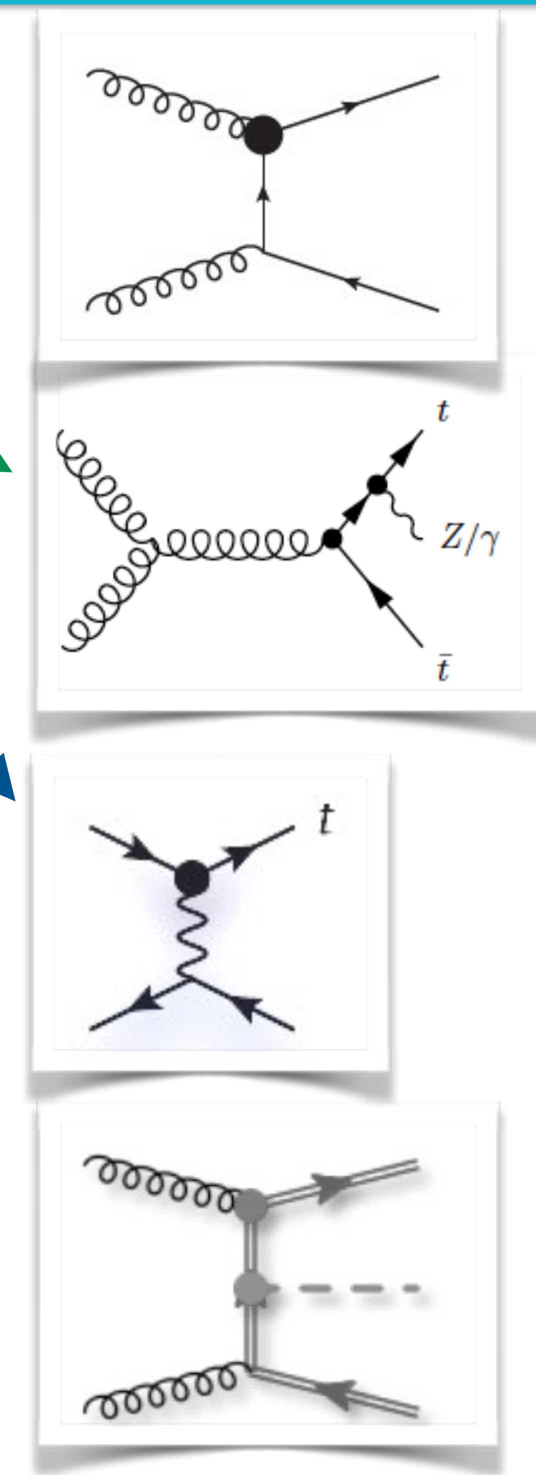

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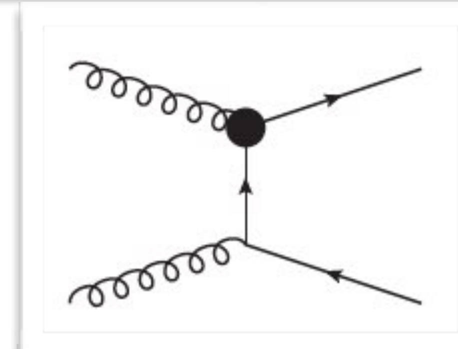

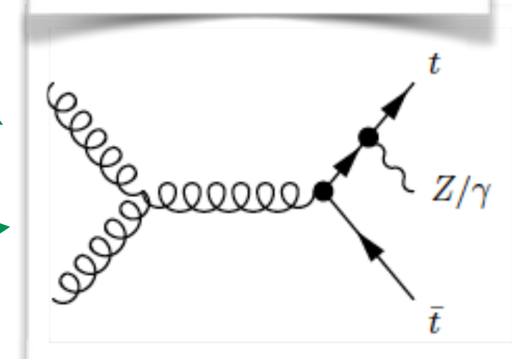

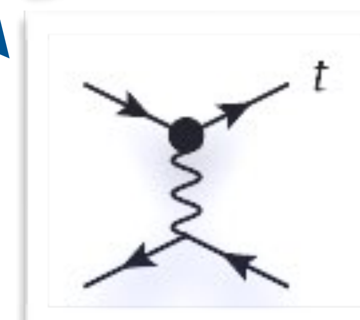

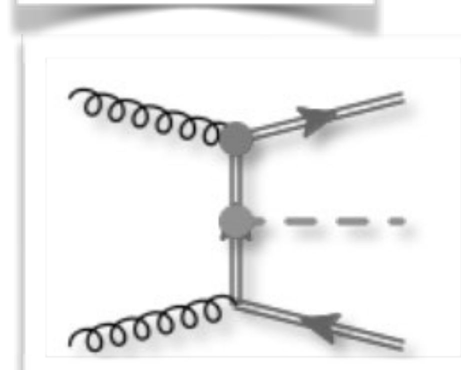

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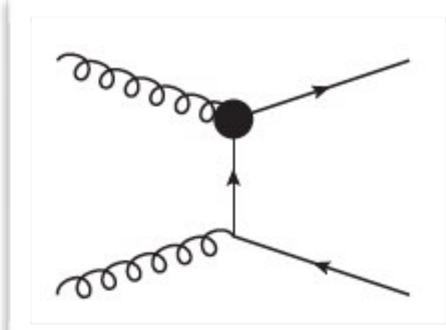

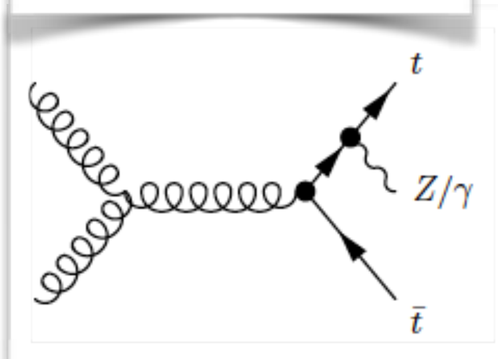

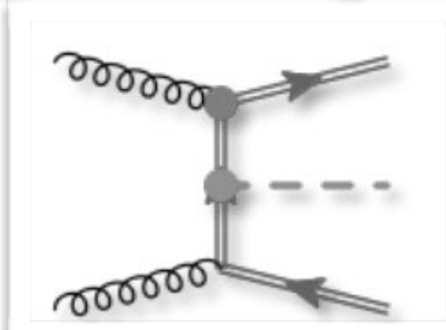

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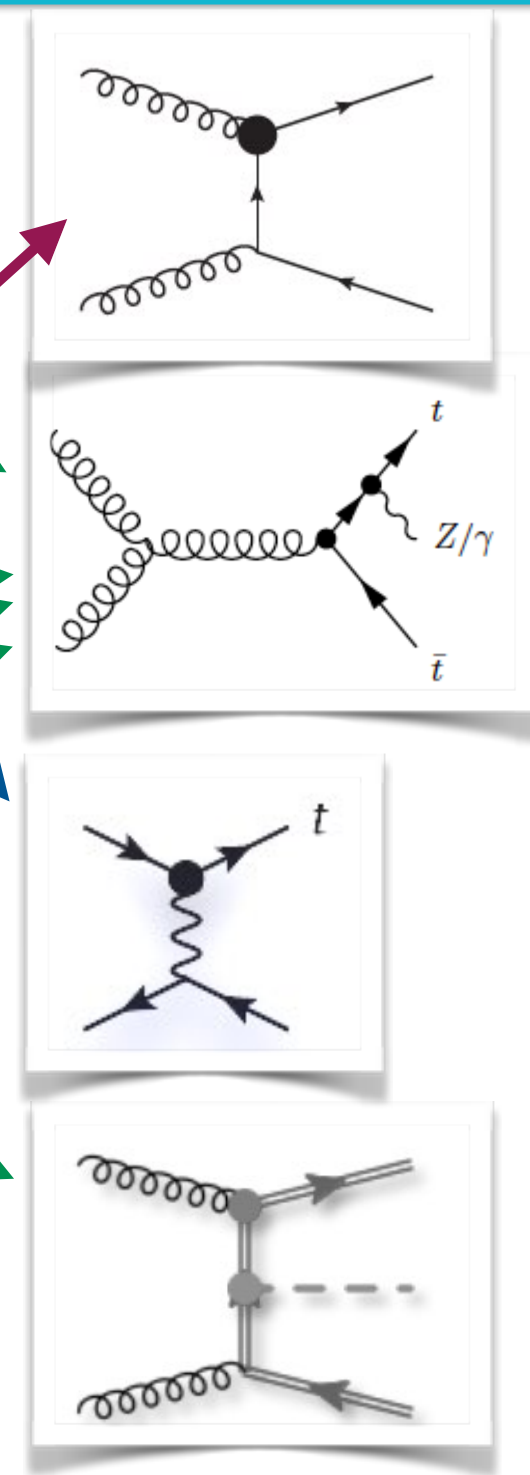

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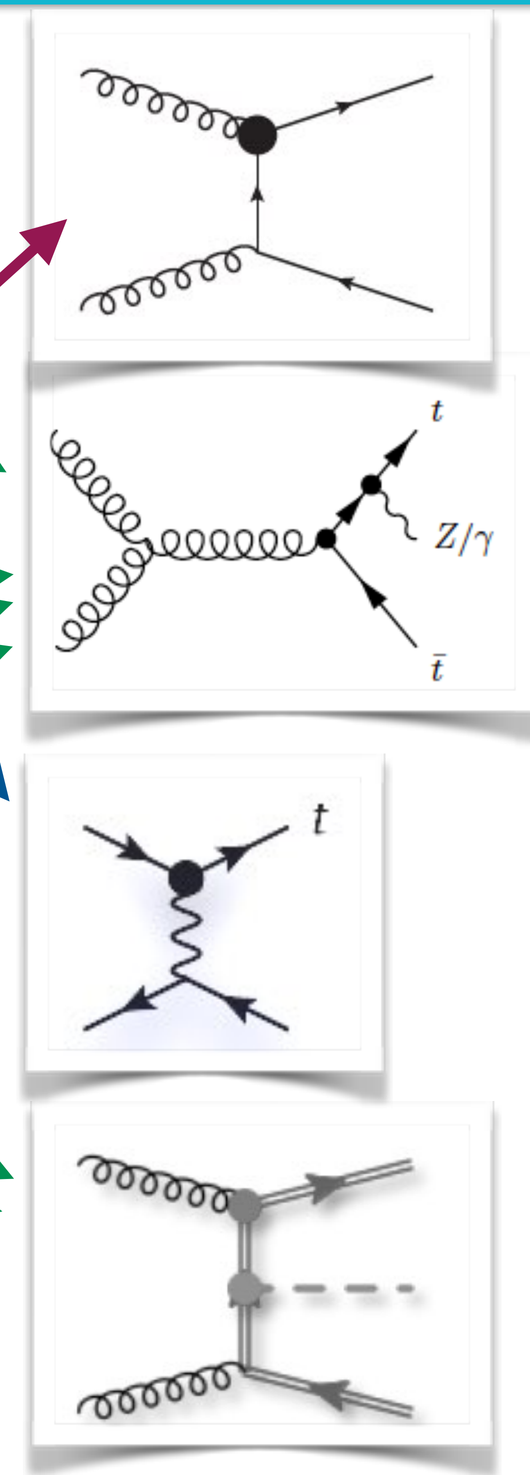

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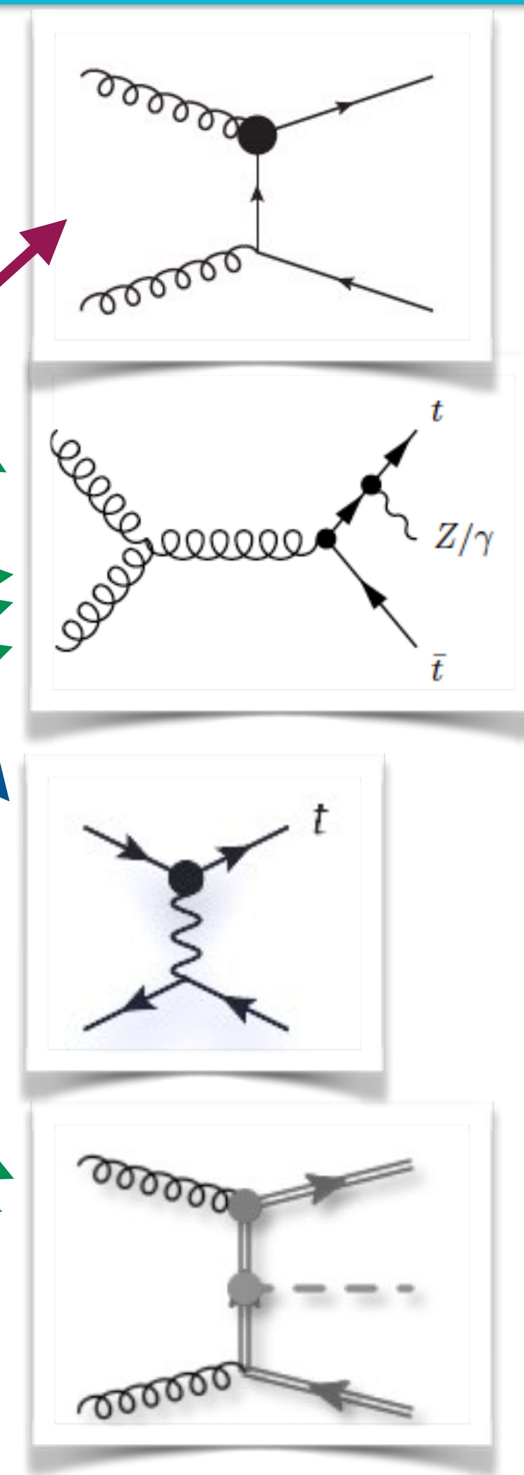

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+non-top operators (mixing)

Operators entering various processes: A strategy is needed

Input from the LHCTopWG

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

J. A. Aguilar Saavedra,[1] C. Degrande,[2] G. Durieux,[3]
F. Maltoni,[4] E. Vryonidou,[2] C. Zhang[5] (editors),
D. Barducci,[6] I. Brivio,[7] V. Cirigliano,[8] W. Dekens,[8,9] J. de Vries,[10] C. Englert,[11]
M. Fabbrichesi,[12] C. Grojean,[3,13] U. Haisch,[2,14] Y. Jiang,[7] J. Kamenik,[15,16]
M. Mangano,[2] D. Marzocca,[12] E. Mereghetti,[8] K. Mimasu,[4] L. Moore,[4] G. Perez,[17]
T. Plehn,[18] F. Riva,[2] M. Russell,[18] J. Santiago,[19] M. Schulze,[13] Y. Soreq,[20]
A. Tonero,[21] M. Trott,[7] S. Westhoff,[18] C. White,[22] A. Wulzer,[2,23,24] J. Zupan.[25]

→ Input from a lot of theorists

Abstract

This note proposes common standards and prescriptions for the effective-field-theory interpretation of top-quark measurements at the LHC.

arXiv:1802.07237

Top EFT note

Contents

Warsaw basis

3 scenarios with different flavour assumptions

Constraints from LHC, EWPO, indirect constraints

Public UFO implementations and benchmark results already given for LHC13

Separate discussion of FCNC

arXiv:1802.07237

Public UFO for top EFT

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

Benchmark results for 13 TeV

		$pp \to t\bar{t}$	$pp \to t\bar{t}\,b\bar{b}$	$pp \to t\bar{t}\,t\bar{t}$	$pp \to t\bar{t}\,e^+\nu$	$pp \to t\bar{t}\,e^+e^-$	$pp \to t\bar{t}\,\gamma$	$pp \to t\bar{t}\,h$
SM	sm	5.2×10^2 pb	1.9 pb	0.0098 pb	0.02 pb	0.016 pb	1.4 pb	0.4 pb
c_{QQ}^1	cQQ1	-0.25	-1.9	-1×10^2		-1.6	-0.67	-0.71
c_{QQ}^8	cQQ8	-0.16	-3.2	-34		-0.91	-0.5	-0.27
c_{Qt}^1	cQt1	-0.15	-5.6	1×10^2		-0.76	-0.19	-0.55
c_{Qt}^8	cQt8	-0.053	-1.8	-41		-0.18	-0.095	-0.15
c_{Qb}^1	cQb1	-0.0055	0.72	-0.052		-0.015	-0.007	-0.026
c_{Qb}^8	cQb8	0.14	3.9	0.12		0.35	0.16	0.56
c_{tt}^1	ctt1			-1.8×10^2				
c_{tb}^1	ctb1	-0.0095	0.46	-0.059		-0.02	-0.026	-0.039
c_{tb}^8	ctb8	0.13	3.5	0.11		0.26	0.31	0.56
c_{QtQb}^1	cQtQb1							
c_{QtQb}^8	cQtQb8							
c_{QtQb}^{1I}	cQtQb1I							
c_{QtQb}^{8I}	cQtQb8I							
$c_{Qq}^{3,8}$	cQq83	2.7	-0.11	4.7	-85	-20	8.5	15
$c_{Qq}^{1,8}$	cQq81	12	7.1	25	2.6×10^2	71	40	75
c_{tq}^8	ctq8	13	8.2	27	2.6×10^2	62	51	74
c_{Qu}^8	cQu8	7.4	4.4	18		21	41	44
c_{tu}^8	ctu8	7.4	3	16		14	22	45
c_{Qd}^8	cQd8	5	3	11		17	7.3	29
c_{td}^8	ctd8	5	2.1	10		12	10	28
$c_{Qq}^{3,1}$	cQq13	3.3	3	5.8	1.1×10^2	22	11	18
$c_{Qq}^{1,1}$	cQq11	0.94	-1.4	-7.7	-5.9	-5	3	5.4
c_{tq}^1	ctq1	0.65	2.4	-7.9	8.7	0.84	3.7	4.8
c_{Qu}^1	cQu1	0.57	1.5	-5.2		1.5	2.9	4.3
c_{tu}^1	ctu1	1.1	-0.29	-3.8		2.3	3.3	6.6
c_{Qd}^1	cQd1	-0.19	0.55	-4		-0.66	-0.3	-1.4
c_{td}^1	ctd1	-0.37	-1.3	-5		-0.91	-1.3	-2.1
$c_{t\varphi}$	ctp		-0.00035	-9.1	-0.034	-0.0093		-1.2×10^2
$c_{\varphi Q}^-$	cpQM	-0.063	1	-41	-0.76	-1×10^2	-0.13	-0.29
$c_{\varphi Q}^3$	cpQ3	0.68	22	0.065	0.46	3.7	1.5	1.8
$c_{\varphi t}$	cpt	-0.024	2.8	42	-0.36	68	-0.058	-0.16
$c_{\varphi tb}$	cptb							
c_{tW}	ctW	0.98	1	-34	13	1.1	69	9.4
c_{tZ}	ctZ	-0.54	0.028	27	-0.048	-3.6	-55	-4.3
c_{bW}	cbW							
c_{tG}	ctG	2.7×10^2	2.5×10^2	3.8×10^2	2.4×10^2	3.1×10^2	2.4×10^2	8.4×10^2
$c_{t\varphi}^I$	ctpI		-7.3×10^{-7}	0.045	-0.00064	-0.00029		0.045
$c_{\varphi tb}^I$	cptbI							
c_{tW}^I	ctWI	4.8×10^{-6}	0.032	-1.6	-0.19	0.29	0.91	0.031
c_{tZ}^I	ctZI	-1.4×10^{-6}	0.1	-1.2	0.0098	3.2	-0.56	-0.057
c_{bW}^I	cbWI							
c_{tG}^I	ctGI	-0.00098	0.48	0.66	0.031	-0.7	0.019	-2.4
$c_{Ql}^{3(1)}$	cQl31				0.011	0.06		
$c_{Ql}^{-(1)}$	cQlM1				-0.0062	-9.8		
$c_{Qe}^{(1)}$	cQe1					-1.5		
$c_{tl}^{(1)}$	ctl1				-0.0023	-3.6		
$c_{te}^{(1)}$	cte1					-6.7		

arXiv:1802.07237

Results at 13 TeV for all degrees of freedom for each process including interference ($1/\Lambda^2$) and squared terms ($1/\Lambda^4$), interference between operators

Public UFO for top EFT

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

How do we proceed?

Use SMEFT to parametrise
and look for deviations
from SM predictions

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We need to identify the most sensitive observables

We need the best SM predictions with QCD/EW corrections

We need precise calculations for the EFT

How do we proceed?

Use SMEFT to parametrise and look for deviations from SM predictions

Use as many experimental measurements as possible Cross-sections and differential distributions

We need to identify the most sensitive observables

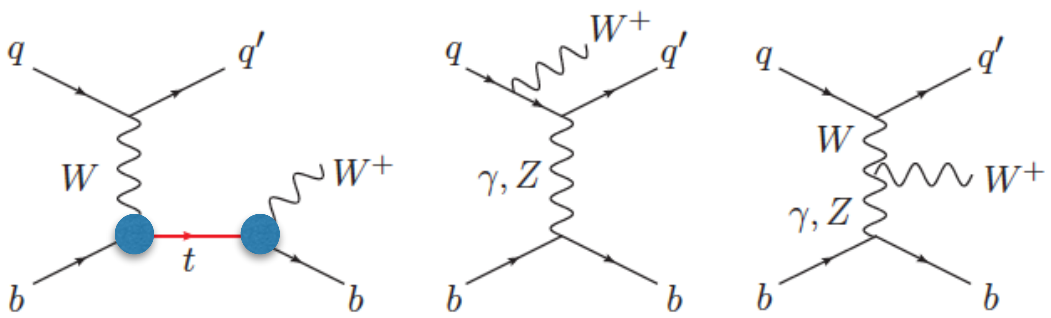
We need the best SM predictions with QCD/EW corrections

We need precise calculations for the EFT

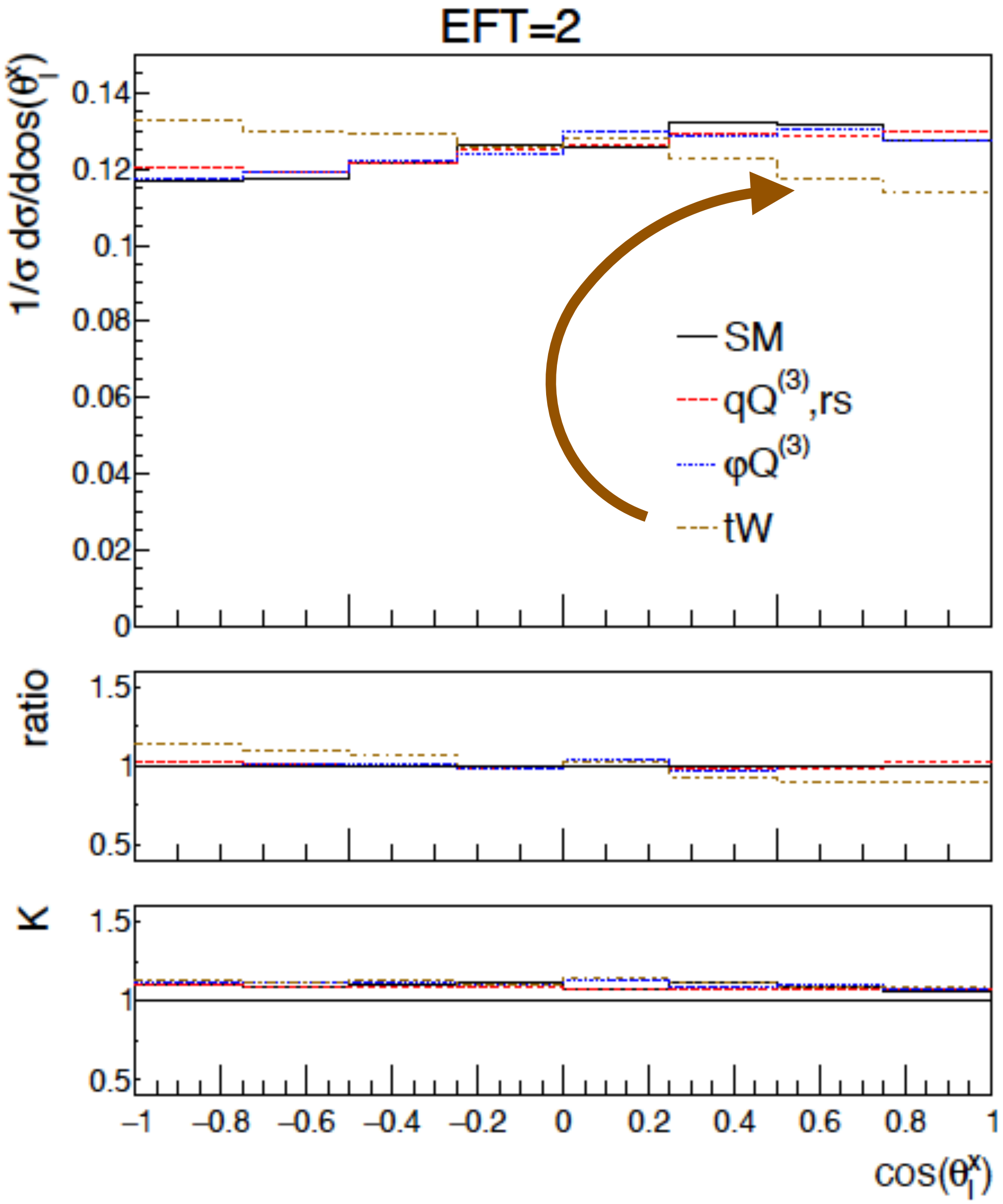
Single top production and decay

Going beyond the narrow width approximation for single top:

- Wbj production with off-shell and interference effects



- Resonant-aware matching to the Parton Shower (arXiv:1603.01178)
- W decay in MadSpin allows us to look at spin-sensitive observables

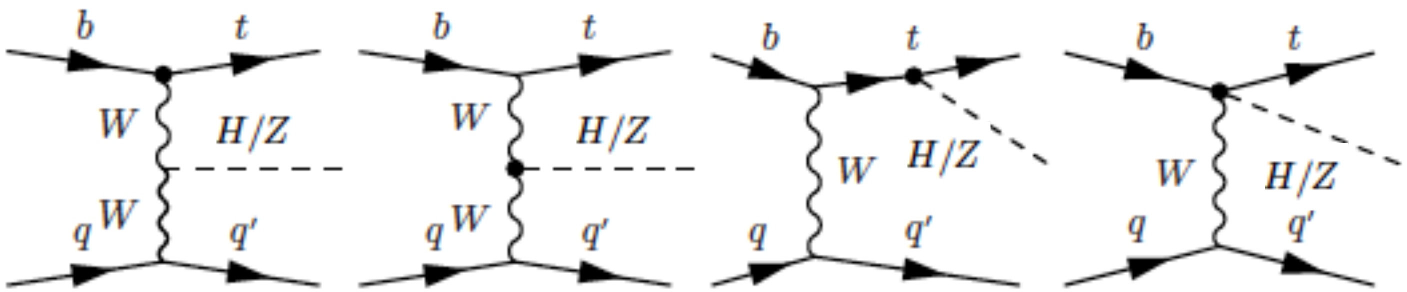


top polarisation angles

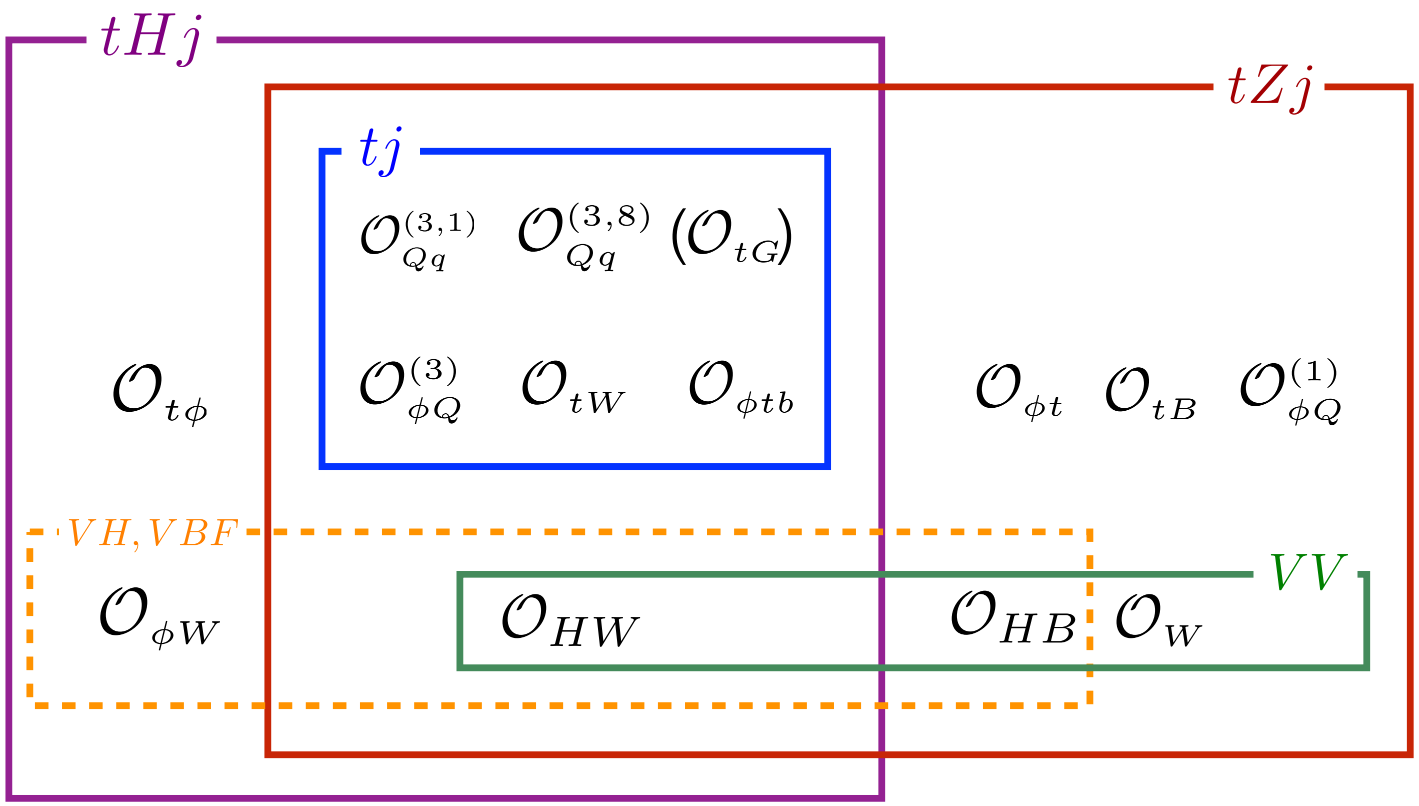
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i^z} = \frac{1}{2}\left(1 + a_i P \cos\theta_i^z\right)$$

de Beurs, Laenen, Vreeswijk, EV arXiv:1807.03576

Rare processes: tZj/tHj associated production



Gauge-Higgs
Top couplings
TGC



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

Unique interplay

Pure gauge operators (4): $\mathcal{O}_{\varphi W}, \mathcal{O}_{W}, \mathcal{O}_{HW}, \mathcal{O}_{HB}$,

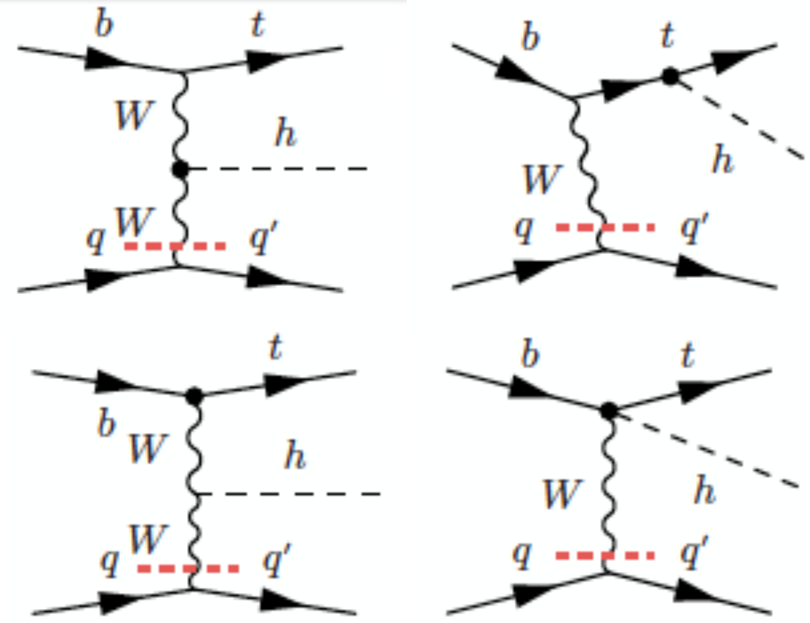
Two-fermion top-quark operators (8): $\mathcal{O}^{(3)}_{\varphi Q}, \mathcal{O}^{(1)}_{\varphi Q}, \mathcal{O}_{\varphi t}, \mathcal{O}_{tW}, \mathcal{O}_{tB}, \mathcal{O}_{tG}, \mathcal{O}_{\varphi tb}, \mathcal{O}_{t\varphi}$

Four-fermion top-quark operators (2): $\mathcal{O}^{(3,1)}_{Qq}, \mathcal{O}^{(3,8)}_{Qq}$.

Helicity amplitudes for subprocesses

$bW \to tH$

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



$bW \to tZ$

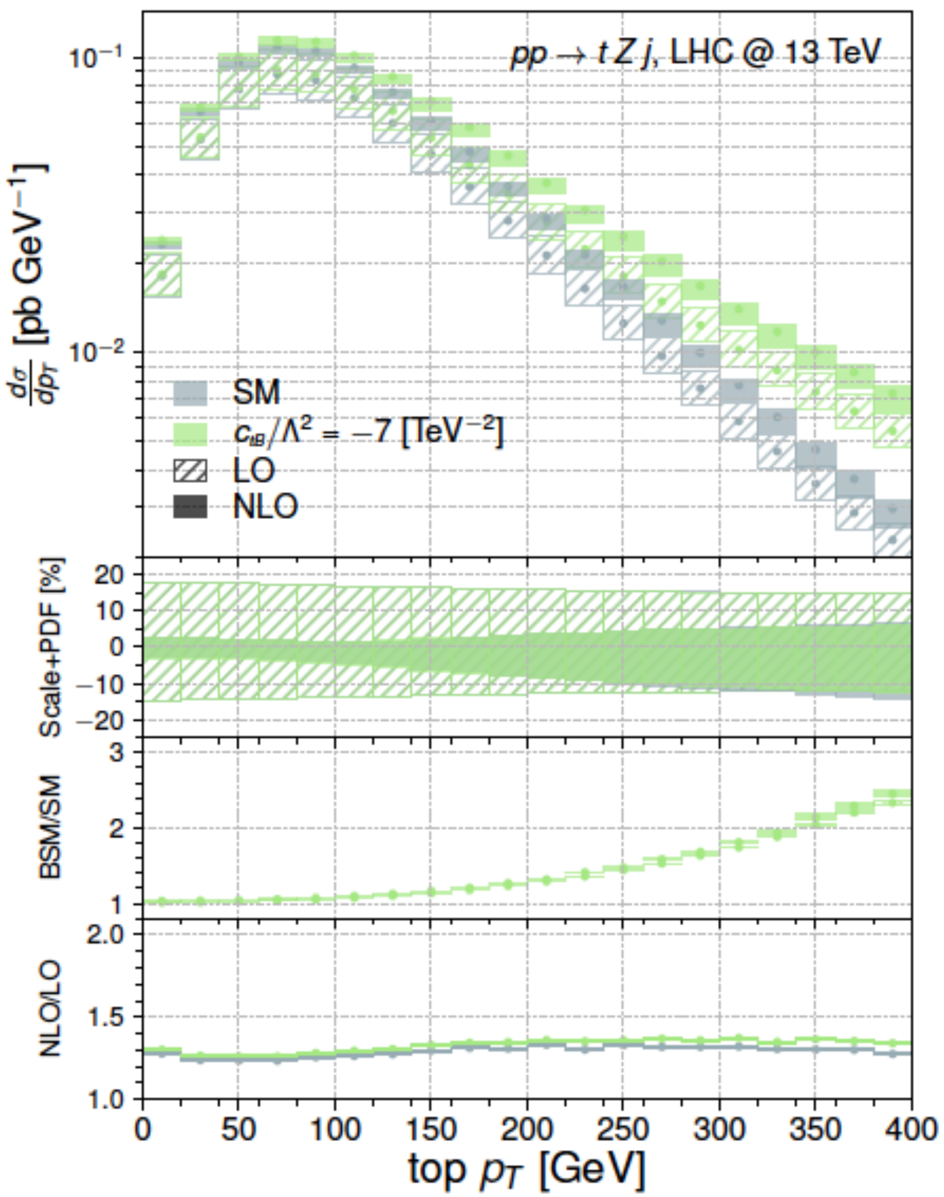
$\lambda_b, \lambda_W, \lambda_t, \lambda_Z$	SM	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{W}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$
$-,0,-,0$	s^0	$\sqrt{s(s+t)}$	$-$	$-$	$-$	s^0	s^0	$\sqrt{s(s+t)}$	s^0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

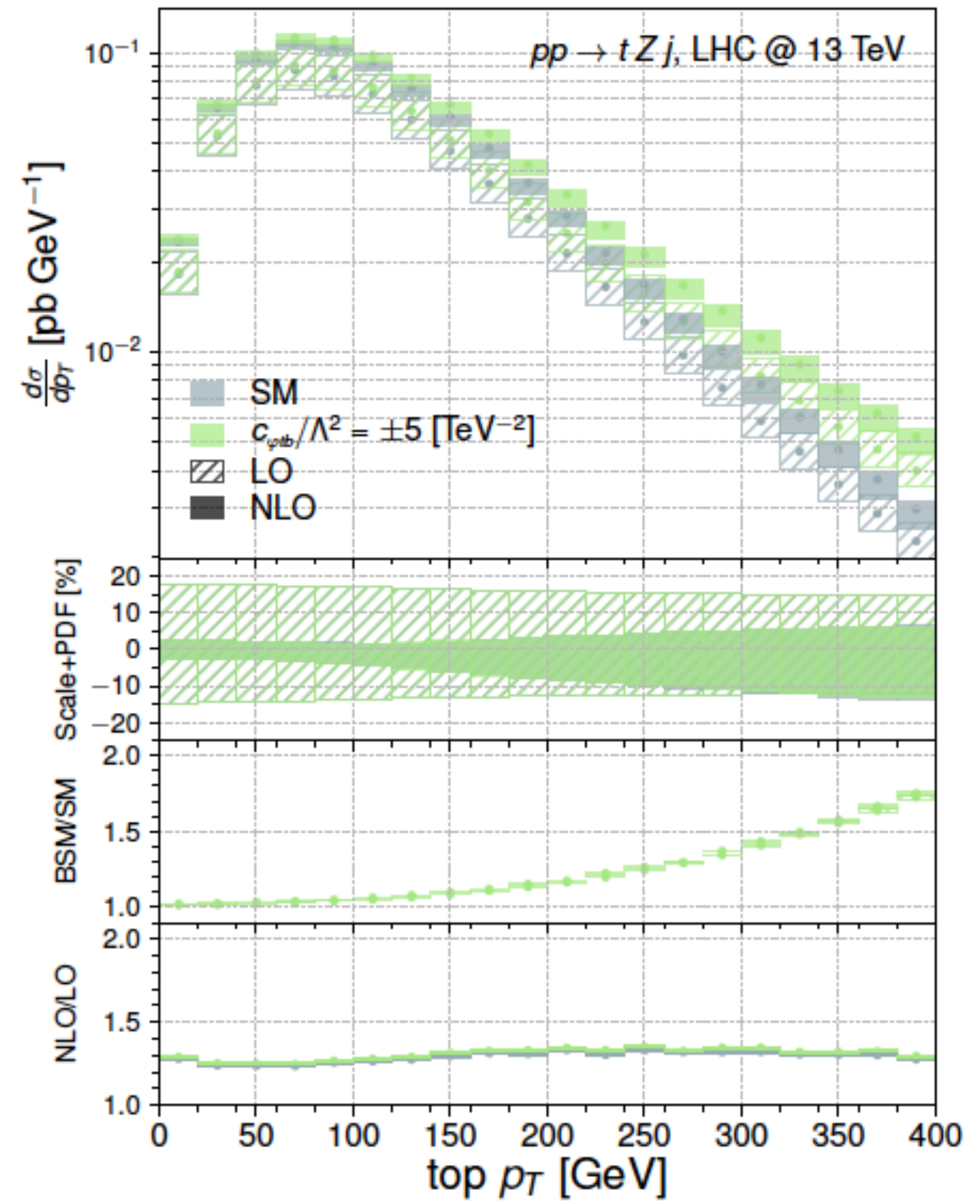
Amplitudes growing with energy as SM cancellations get spoiled ➡

Large deviations
Differential distributions

Differential results

tZj

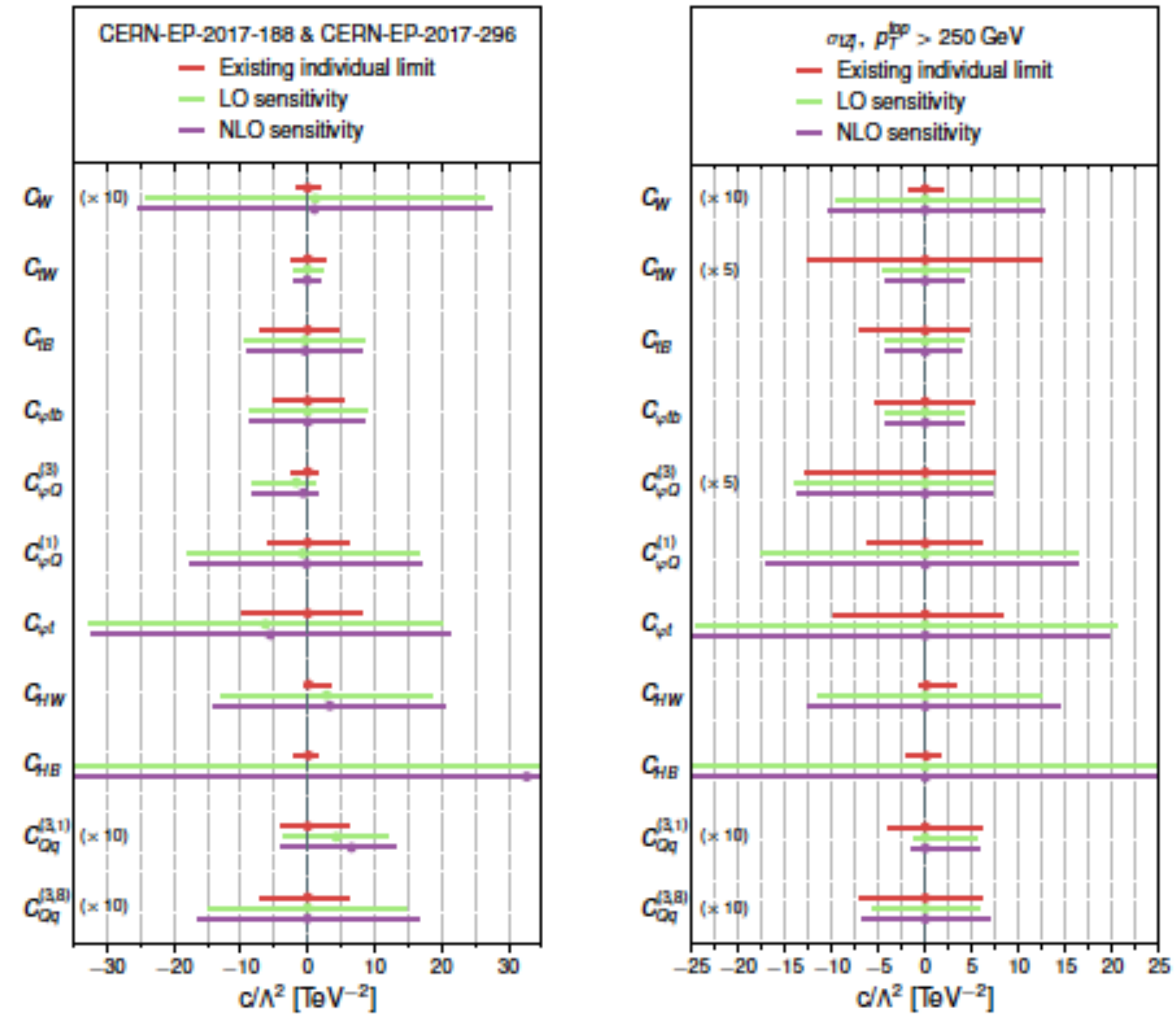




Large deviations in the tails, as expected from helicity amplitudes

Current and future sensitivity

Op.	TF (I)	TF (M)	RHCC (I) tree/loop	σ_{ttH} [10]	SFitter (I)	PEWM[2]
$\mathcal{O}_W$					[-0.18, 0.18]	
$\mathcal{O}_{HW}$					[-0.64,3.25]	
$\mathcal{O}_{HB}$					[-2.11,1.57]	
$\mathcal{O}_{\varphi W}$					[-0.39,0.33]	
$\mathcal{O}_{\varphi tb}$			[-5.28,5.28]/[-0.046,0.040]			
$\mathcal{O}_{\varphi Q}^{(3)}$	[-2.59,1.50]	[-4.19,2.00]				-1.0 ± 2.7 [3]
$\mathcal{O}_{\varphi Q}^{(1)}$	[-3.10,3.10]					1.0 ± 2.7
$\mathcal{O}_{\varphi t}$	[-9.78,8.18]					1.8 ± 3.8
$\mathcal{O}_{tW}$	[-2.49,2.49]	[-3.99,3.40]				-0.4 ± 2.4
$\mathcal{O}_{tB}$	[-7.09,4.68]					4.8 ± 10.6
$\mathcal{O}_{tG}$	[-0.24,0.53]	[-1.07,0.99]				
$\mathcal{O}_{t\varphi}$				[-6.5,1.3]	[-18.2,6.30]	
$\mathcal{O}_{Qq}^{(3,1)}$	[-0.40,0.60]	[0.66,1.24]				
$\mathcal{O}_{Qq}^{(3,8)}$	[-4.90,3.70]	[6.06,6.73]				



TopFitter: Buckley et al. arXiv:1512.03360
SFitter: Butter et al. arXiv:1604.03105
PEWM: Zhang et al. arXiv:1201.6670
ttH: Maltoni et al. arXiv:1607.05330
RHCC: Alioli et al. arXiv:1703.04751

tZj measurements:
CMS; PLB 779 (2018) 358-384: 0.75 ± 0.27
ATLAS; CERN-EP-2017-188: 1.31 ± 0.47

Promising for weak dipoles, RHCC and SU(2) current in particular for HL-LHC where high pT data can potentially be used

Rare processes can play a role in a global fit

Towards a complete implementation@NLO

Based on:

- Warsaw basis
- Degrees of freedom for top operators as in dim6top

Current status:

- 73 degrees of freedom (top, Higgs, gauge):
  - CP-conserving
  - Flavour assumption: $U(2)_Q \times U(2)_u \times U(3)_d \times U(3)_L \times U(3)_e$
- Successful validation at LO with dim6top (in turn validated with SMEFTsim)
- 0/2F@NLO operators validated (with previous partial NLO implementations) → **http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO**
- 4F@NLO operators validation: on-going

Future plans

- Full NLO model release (4F@NLO)
- Other flavour assumptions
- CP-violating effects

Work in progress with:
C. Degrande, G. Durieux, F. Maltoni, K. Mimasu, C. Zhang

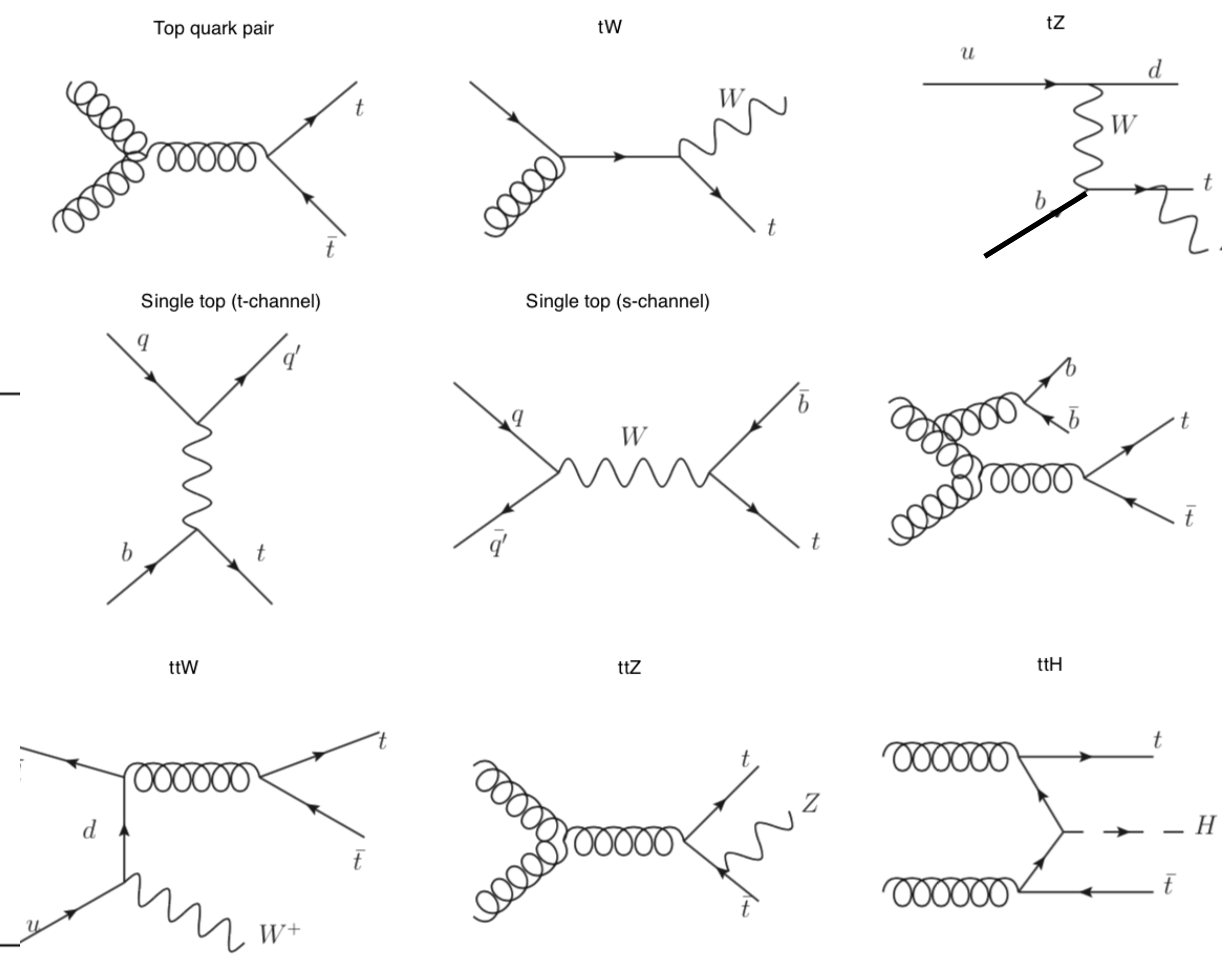
Outline

- Top EFT: recent theory progress
- **Global top EFT fit**

A global top fit@NLO

Class	Notation	Degree of Freedom	Operator Definition	Sensitivity at $\mathcal{O}(\Lambda^{-2})$ ($\mathcal{O}(\Lambda^{-4})$) $t\bar{t}$	single-top	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
	OQQ1	c^1_{QQ}	$2C^{1(3333)}_{qq} - \frac{2}{3}C^{3(3333)}_{qq}$								✓	✓
	OQQ8	c^8_{QQ}	$8C^{3(3333)}_{qq}$								✓	✓
	OQt1	c^1_{Qt}	$C^{1(3333)}_{qu}$								✓	✓
	OQt8	c^8_{Qt}	$C^{8(3333)}_{qu}$								✓	✓
$QQQQ$	OQb1	c^1_{Qb}	$C^{1(3333)}_{qd}$									✓
	OQb8	c^8_{Qb}	$C^{8(3333)}_{qd}$									✓
	Ott1	c^1_{tt}	$C^{(3333)}_{uu}$								✓	
	Otb1	c^1_{tb}	$C^{1(3333)}_{ud}$									✓
	Otb8	c^8_{tb}	$C^{8(3333)}_{ud}$									✓
	OQtQb1	c^1_{QtQb}	$C^{1(3333)}_{quqd}$									✓
	OQtQb8	c^8_{QtQb}	$C^{8(3333)}_{quqd}$									✓
	O81qq	$c^{1,8}_{Qq}$	$C^{1(i33i)}_{qq} + 3C^{3(i33i)}_{qq}$	✓				✓	✓	✓	✓	✓
	O11qq	$c^{1,1}_{Qq}$	$C^{1(ii33)}_{qq} + \frac{1}{6}C^{1(i33i)}_{qq} + \frac{1}{2}C^{3(i33i)}_{qq}$	(✓)				(✓)	(✓)	(✓)	✓	✓
	O83qq	$c^{3,8}_{Qq}$	$C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}$	✓	(✓)		(✓)	✓	✓	✓	✓	✓
	O13qq	$c^{3,1}_{Qq}$	$C^{3(ii33)}_{qq} + \frac{1}{6}(C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq})$	(✓)	✓		✓	(✓)	(✓)	(✓)	✓	✓
	O8qt	c^8_{tq}	$C^{8(ii33)}_{qu}$	✓				✓	✓	✓	✓	✓
	O1qt	c^1_{tq}	$C^{1(ii33)}_{qu}$	(✓)				(✓)	(✓)	(✓)	✓	✓
$QQqq$	O8ut	c^8_{tu}	$2C^{(i33i)}_{uu}$	✓					✓	✓	✓	✓
	O1ut	c^1_{tu}	$C^{(ii33)}_{uu} + \frac{1}{3}C^{(i33i)}_{uu}$	(✓)					(✓)	(✓)	✓	✓
	O8qu	c^8_{Qu}	$C^{8(33ii)}_{qu}$	✓					✓	✓	✓	✓
	O1qu	c^1_{Qu}	$C^{1(33ii)}_{qu}$	(✓)					(✓)	(✓)	✓	✓
	O8dt	c^8_{td}	$C^{8(33ii)}_{ud}$	✓					✓	✓	✓	✓
	O1dt	c^1_{td}	$C^{1(33ii)}_{ud}$	(✓)					(✓)	(✓)	✓	✓
	O8qd	c^8_{Qd}	$C^{8(33ii)}_{qd}$	✓					✓	✓	✓	✓
	O1qd	c^1_{Qd}	$C^{1(33ii)}_{qd}$	(✓)					(✓)	(✓)	✓	✓
	OtG	c_{tG}	$\mathrm{Re}\{C^{(33)}_{uG}\}$	✓		✓		✓	✓	✓	✓	✓
	OtW	c_{tW}	$\mathrm{Re}\{C^{(33)}_{uW}\}$		✓	✓	✓					
	ObW	c_{bW}	$\mathrm{Re}\{C^{(33)}_{dW}\}$		(✓)	(✓)	(✓)					
	OtZ	c_{tZ}	$\mathrm{Re}\{-s_W C^{(33)}_{uB} + c_W C^{(33)}_{uW}\}$				✓		✓			
$QQ+V,G,\varphi$	Off	$c_{\varphi tb}$	$\mathrm{Re}\{C^{(33)}_{\varphi ud}\}$		(✓)	(✓)	(✓)					
	Ofq3	$c^3_{\varphi Q}$	$C^{3(33)}_{\varphi q}$		✓	✓	✓					
	OpQM	$c^-_{\varphi Q}$	$C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q}$				✓		✓			
	Opt	$c_{\varphi t}$	$C^{(33)}_{\varphi u}$				✓		✓			
	Otp	$c_{t\varphi}$	$\mathrm{Re}\{C^{(33)}_{u\varphi}\}$							✓		

34 d.o.f.
CP-conserving



Rich phenomenology

Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965

Global fit Setup

Theory

(N)NLO QCD+ NLO EW for SM
NLO QCD for SMEFT
State-of-the-art PDFs without top data

Data

Top pair production and single top (differential)
Associated production with W,Z,H
W helicity fractions
Parton-level

Global SMEFT fit of the top-quark sector

Methodology

Based on NNPDF
Faithful uncertainty estimate
Avoid under- and over-fitting
Validated on pseudo-data (closure test)

Output

Fit results can be used to bound specific UV complete models
New data can be straightforwardly added
Plan to extend to Higgs, gauge sector etc

Observables and theory predictions

Data

Top-pair production
W-helicities

4 tops, ttbb, top-pair associated production

Single top
t-channel, s-channel, tW, tZ

Dataset	n_{dat}
ATLAS_tt_8TeV_ljets [$m_{t\bar{t}}$]	7
CMS_tt_8TeV_ljets [y_t]	10
CMS_tt2D_8TeV_dilep [$(m_{t\bar{t}}, y_t)$]	16
CMS_tt_13TeV_ljets2 [$y_{t\bar{t}}$]	8
CMS_tt_13TeV_dilep [$y_{t\bar{t}}$]	6
CMS_tt_13TeV_ljets_2016 [y_t]	11
ATLAS_WhelF_8TeV	3
CMS_WhelF_8TeV	3
CMS_ttbb_13TeV	1
CMS_tttt_13TeV	1
ATLAS_tth_13TeV	1
CMS_tth_13TeV	1
ATLAS_ttZ_8TeV	1
ATLAS_ttZ_13TeV	1
CMS_ttZ_8TeV	1
CMS_ttZ_13TeV	1
ATLAS_ttW_8TeV	1
ATLAS_ttW_13TeV	1
CMS_ttW_8TeV	1
CMS_ttW_13TeV	1
CMS_t_tch_8TeV_dif	6
ATLAS_t_tch_8TeV [y_t]	4
ATLAS_t_tch_8TeV [y_t]	4
ATLAS_t_sch_8TeV	1
CMS_t_tch_13TeV_dif [y_t]	4
CMS_t_sch_8TeV	1
ATLAS_tW_inc_8TeV	1
CMS_tW_inc_8TeV	1
ATLAS_tW_inc_13TeV	1
CMS_tW_inc_13TeV	1
ATLAS_tZ_inc_13TeV	1
CMS_tZ_inc_13TeV	1
Total	102

One distribution from each dataset, to avoid double counting

Theoretical predictions

Process	SM	SMEFT
$t\bar{t}$	NNLO QCD	NLO QCD
single-t (t-ch)	NNLO QCD	NLO QCD
single-t (s-ch)	NLO QCD	NLO QCD
tW	NLO QCD	NLO QCD
tZ	NLO QCD	LO QCD + NLO SM K-factors
$t\bar{t}W(Z)$	NLO QCD	LO QCD + NLO SM K-factors
$t\bar{t}h$	NLO QCD	LO QCD + NLO SM K-factors
$t\bar{t}t\bar{t}$	NLO QCD	LO QCD + NLO SM K-factors
$t\bar{t}b\bar{b}$	NLO QCD	LO QCD + NLO SM K-factors

Baseline fit includes:

- Best available SM predictions
- NLO EFT predictions
- $O(1/\Lambda^4)$ terms

Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965

Methodology

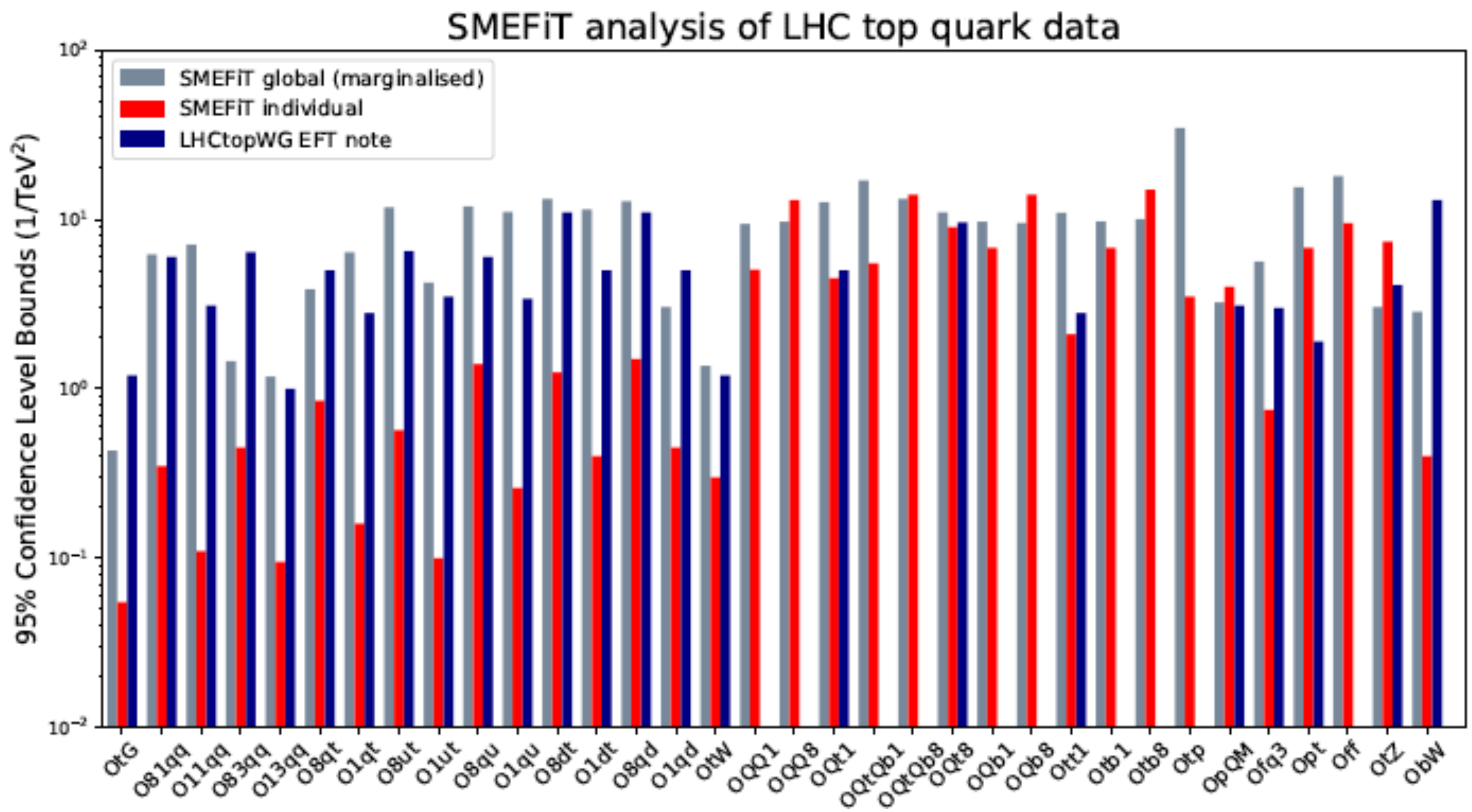
- Based on the MC replica method used by NNPDF for PDF fits
  - Construct sampling of the probability distribution in the data space.
  - Sampling of the probability distribution in the SMEFT space by minimising the error function.

$$E(\{c_l^{(k)}\}) \equiv \frac{1}{N_{\rm dat}} \sum_{i,j=1}^{N_{\rm dat}} \left(\mathcal{O}_i^{(\rm th)}\left(\{c_l^{(k)}\}\right) - \mathcal{O}_i^{(\rm art)(k)}\right) ({\rm cov}^{-1})_{ij} \left(\mathcal{O}_j^{(\rm th)}\left(\{c_l^{(k)}\}\right) - \mathcal{O}_j^{(\rm art)(k)}\right)$$

- Cross validation to avoid over-fitting: for each replica, the data is randomly split with equal probability into the training and validation sets. The latter is monitored during the fit, to avoid over-fitting.

- Closure test: feed pseudo-data generated with known EFT parameters to the fit, and ensure that the fit reproduces the correct parameters.

Global top EFT fit@NLO



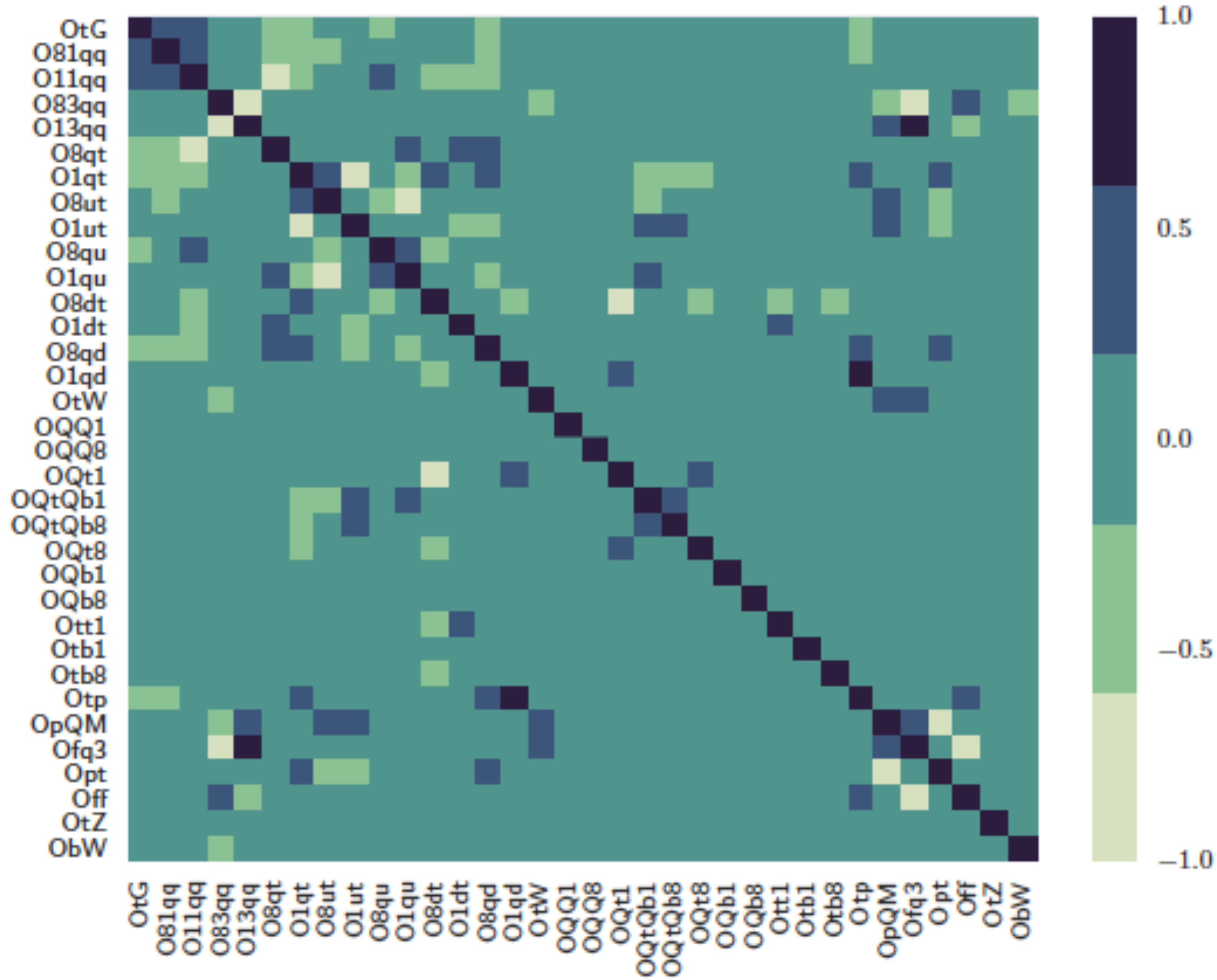
First limits reported for some operators

Improvement for some operators: e.g. O_{tG}, O^{83}_{qq}, O_{bW}

Individual limits more stringent than marginalised ones

Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965

Correlations between EFT coefficients



Strong (anti-)correlations between different operators (ignored by individual constraints)

Some fit considerations

- $1/\Lambda^2$ vs $1/\Lambda^4$ contributions
  - $1/\Lambda^2$ suppressed due to helicity Azatov et al arXiv:1607.05236 or colour (for example 4-fermion operators in top pair production)
  - $1/\Lambda^4$ can be large for loosely constrained operator coefficients/strongly coupled theories

$$C_i^2 \frac{E^4}{\Lambda^4} > C_i \frac{E^2}{\Lambda^2} > 1 > \frac{E^2}{\Lambda^2}$$

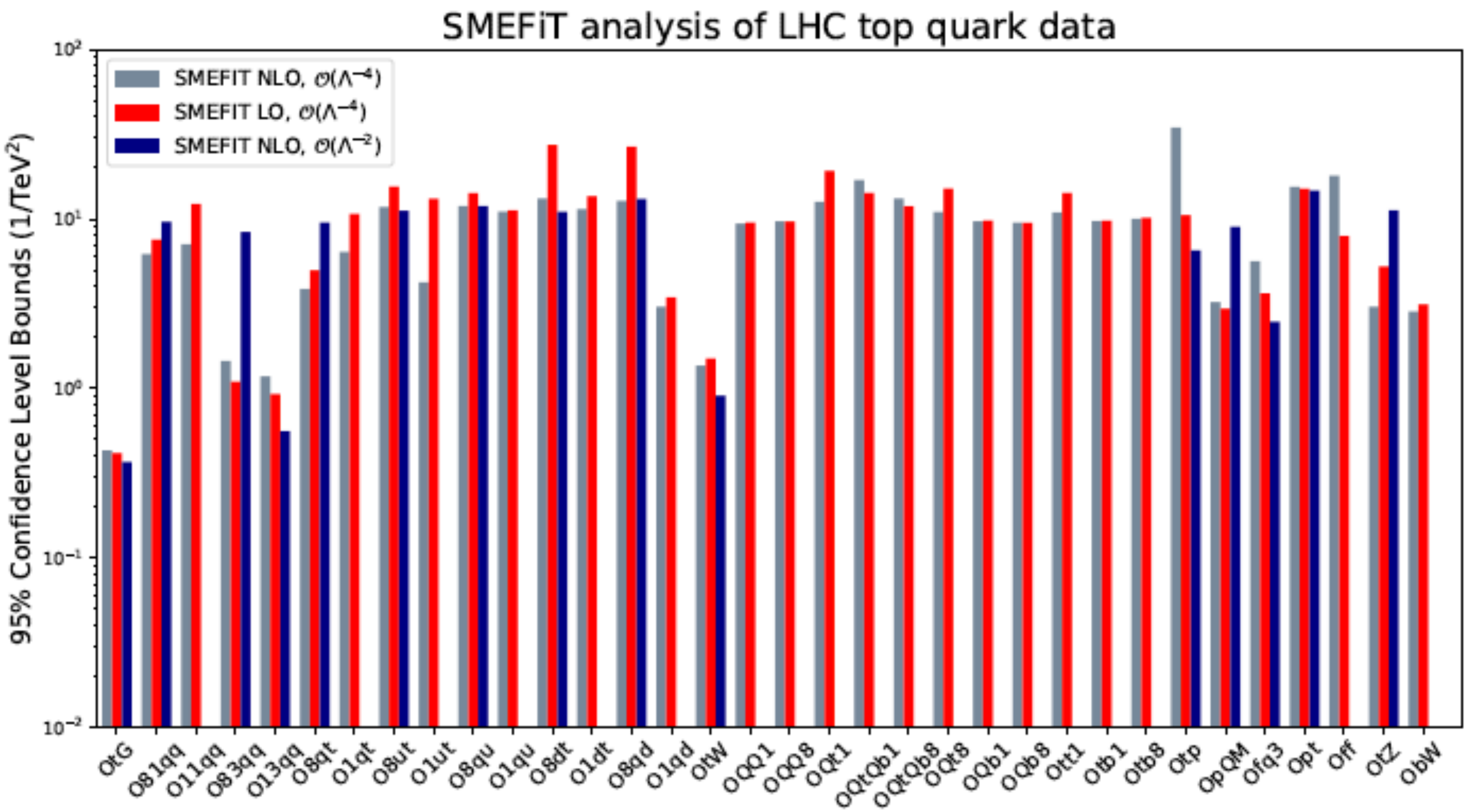
E<Λ satisfied but $O(1/\Lambda^4)$ large for large operator coefficients

- Validity of the EFT expansion: E<Λ
  - Ensure results are not dominated by high energy regions
  - report limits as a function of the max scale probed Contino et al arXiv:1604.06444

Need to have control on these effects

Impact of higher-order terms

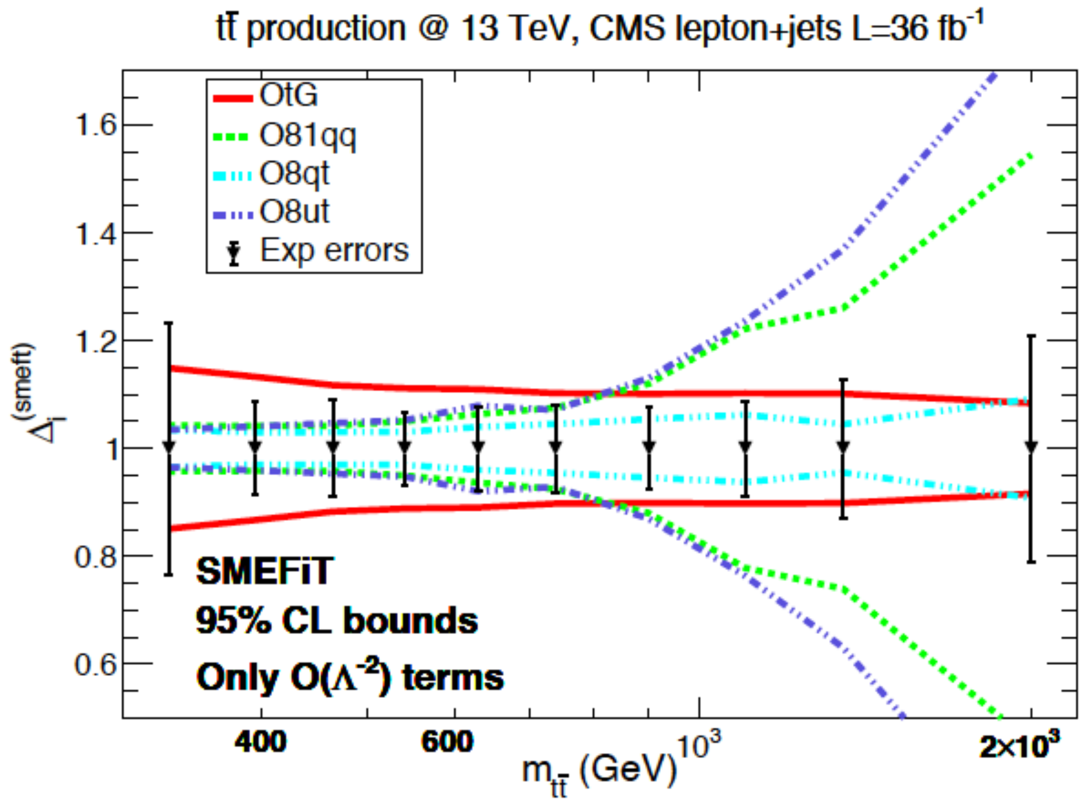
Fit allows to check the impact of NLO QCD corrections and of including the $O(1/\Lambda^4)$ terms

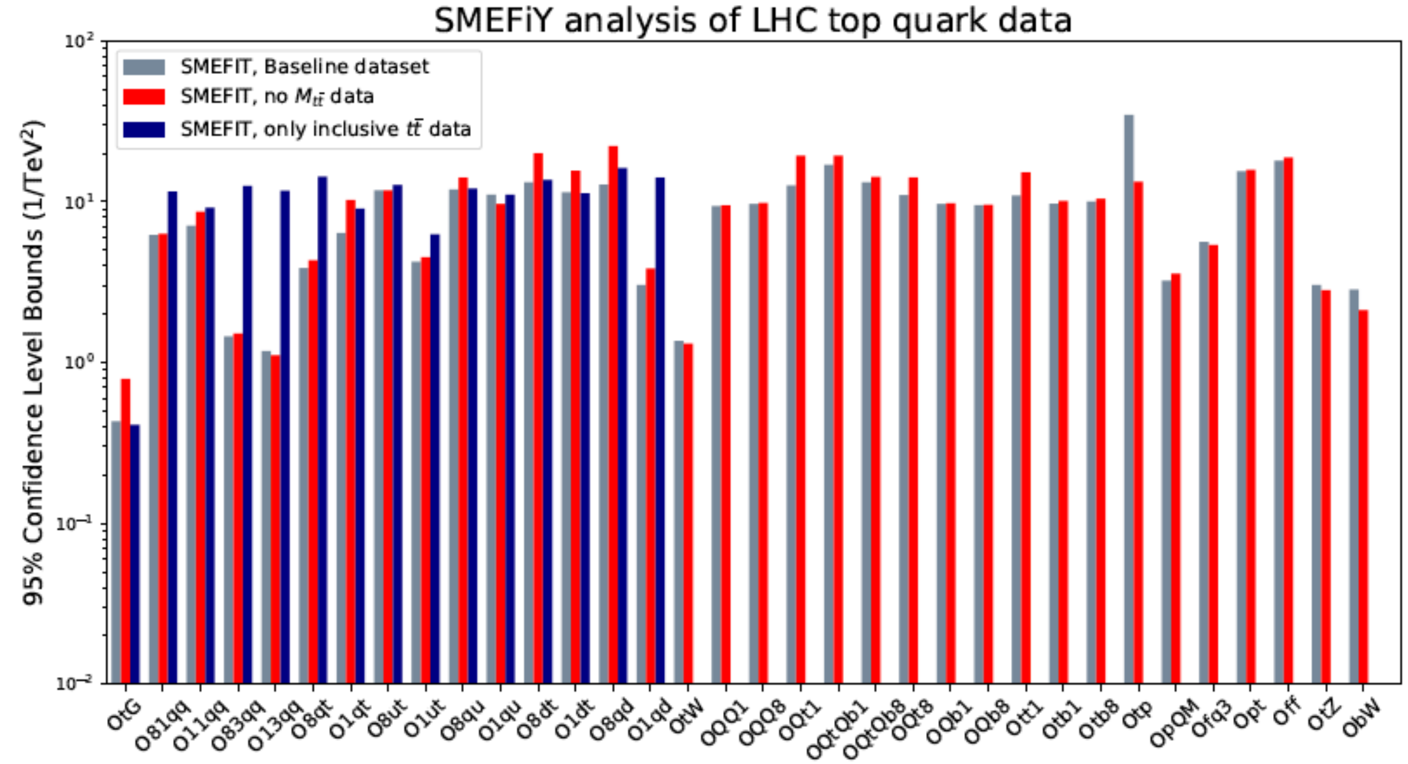


Non-trivial impact of the two effects, can be different operator-by-operator, some operators can only be constrained at $O(1/\Lambda^4)$

Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965

High-energy behaviour





m_{tt} distribution has bins above 1 TeV → Use y_{tt} as a check

Need to always take this into account for specific choice of Λ

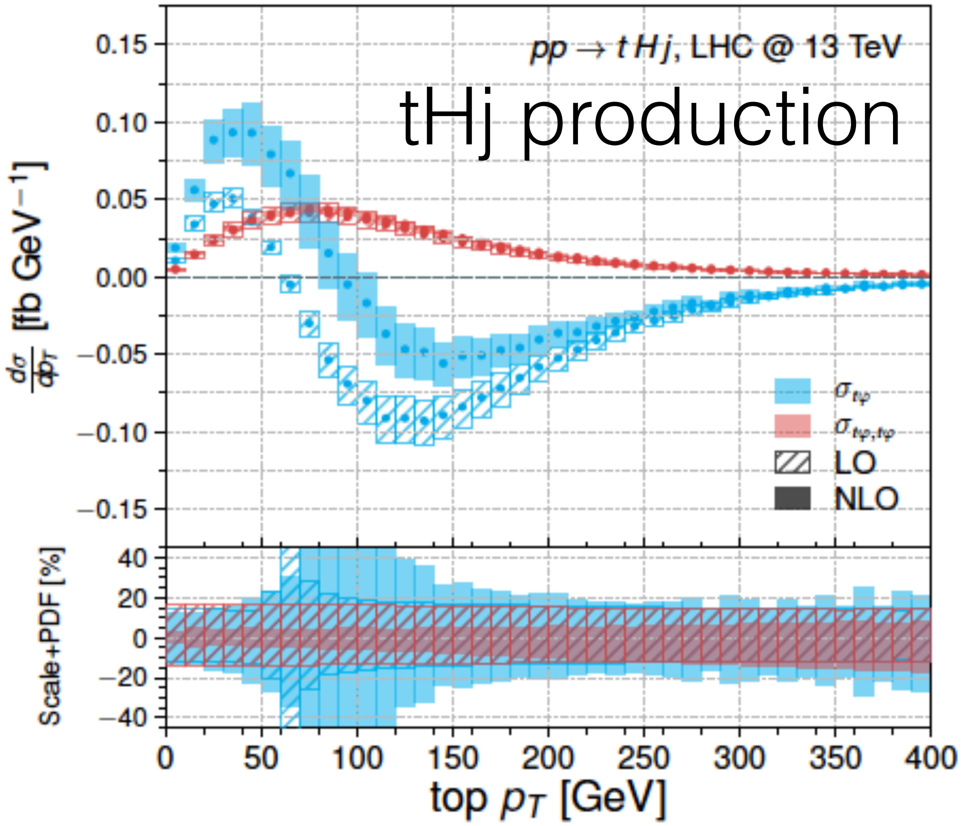
Summary & Outlook

- NLO SMEFT implementation:
  - Public release of SMEFT@NLO with 73 d.o.f's
    - **http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO**
  - Extensively validated and user friendly
- First application of the NLO implementation:
  - A global fit in the top sector
    - NLO SMEFT predictions
    - Wide range of LHC top data
    - Robust and reliable fitting procedure based on NNPDF methodology
- Extension of the fit to include EWPO, Higgs, diboson data is straightforward and constitutes the next step
- Fitting UV models a posteriori under study

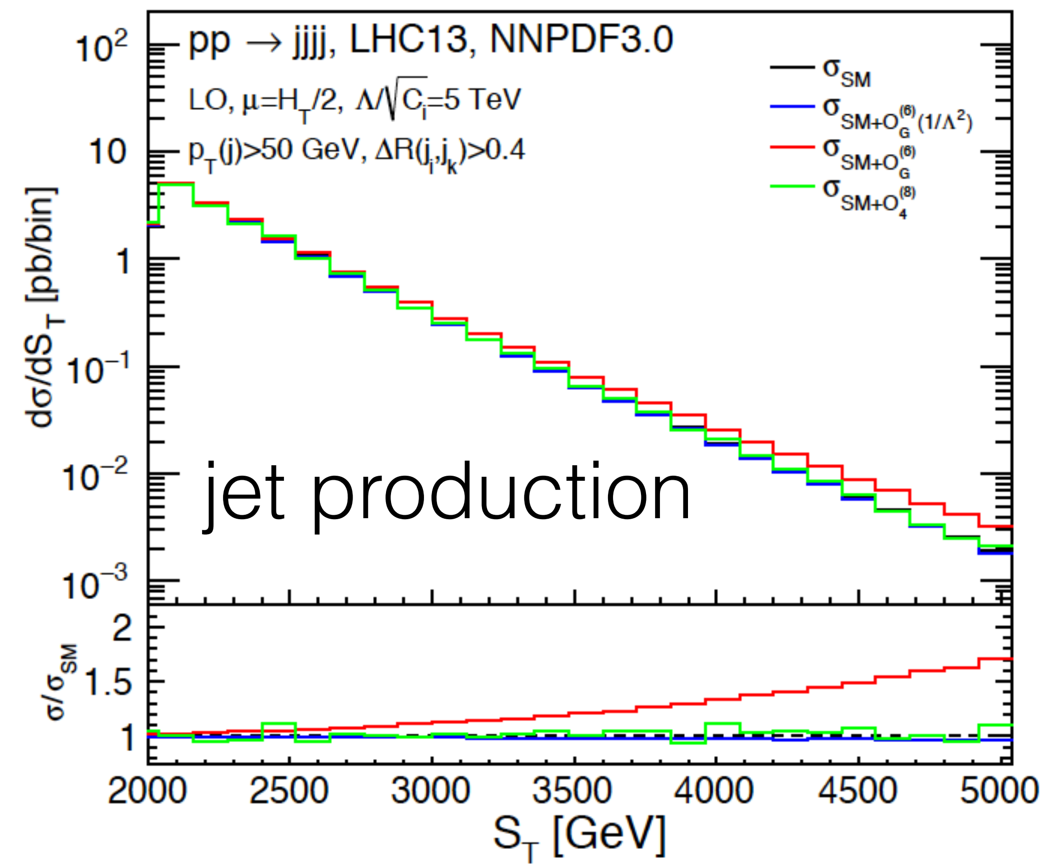
Thanks a lot for your attention

$1/\Lambda^2$ vs $1/\Lambda^4$ contributions some examples

1)



2)



$1/\Lambda^2$ is not positive definite
$1/\Lambda^2$ is not suppressed PS point by PS point
$1/\Lambda^2$ is suppressed only when integrating over the phase space

$1/\Lambda^2$ is suppressed compared to $1/\Lambda^4$
$1/\Lambda^4$ from dimension-6 much larger than interference of SM with dim-8

3) ttZ production

13TeV	$\mathcal{O}_{tW}$
$\sigma^{(1)}_{i,NLO}$	$-1.7(2)^{+31.3\%}_{-49.1\%}$
$\sigma^{(2)}_{ii,NLO}$	$24.2^{+6.2\%}_{-11.2\%}$

Reasons why the interference is suppressed:
1) An accidental cancellation between the contributions of the gg and qq channels
2) OtW not producing a longitudinal Z