Top-quark effective field theory

Fabio Maltoni

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

UCLouvain Belgium

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

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

[Grzadkowski et al, 2010]

- Based on all the symmetries of the SM
- New physics is heavier than any other SM particle $\Lambda > M_{SM}$.
- QCD and EW renormalisable (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 up to the scale Λ.

TopEFT

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011,Degrande et al. 2011]

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

$$O_G = g_s f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$$
$$O_{\varphi G} = g_s^2 \left(\varphi^\dagger\varphi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

4-quark operators

$$O_{QQ}^{(1)} = (\bar{Q}\gamma_\mu Q)(\bar{Q}\gamma^\mu Q)$$
$$O_{QQ}^{(3)} = (\bar{Q}\gamma_\mu \tau^I Q)(\bar{Q}\gamma^\mu \tau^I Q)$$
$$O_{uu} = (\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$$
$$O_{ud}^{(1)} = (\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$$
$$O_{ud}^{(8)} = (\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)$$
$$O_{Qu}^{(1)} = (\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$$
$$O_{Qu}^{(8)} = (\bar{Q}\gamma_\mu T^A Q)(\bar{u}\gamma^\mu T^A u)$$
$$O_{Qd}^{(1)} = (\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$$
$$O_{Qd}^{(8)} = (\bar{Q}\gamma_\mu T^A Q)(\bar{d}\gamma^\mu T^A d)$$
$$O_{QuQd}^{(1)} = (\bar{Q}^j u)\epsilon_{jk}(\bar{Q}^k d)$$
$$O_{QuQd}^{(8)} = (\bar{Q}^j T^A u)\epsilon_{jk}(\bar{Q}^k T^A d)$$

+ 2q2l operator

CP and Flavour conserving operators

Operators and processes

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

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

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

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

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

$$O_{bW} = y_b g_w(\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu}$$

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

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

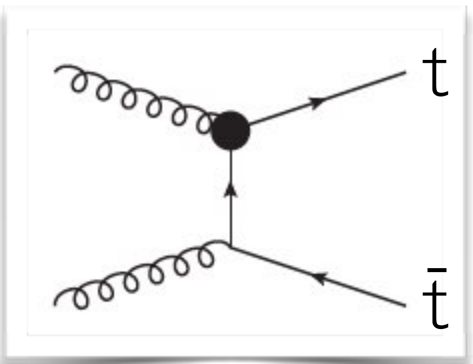
$$O_{t\varphi} = (\varphi^\dagger\varphi)(\bar{Q}t\tilde{\varphi})$$

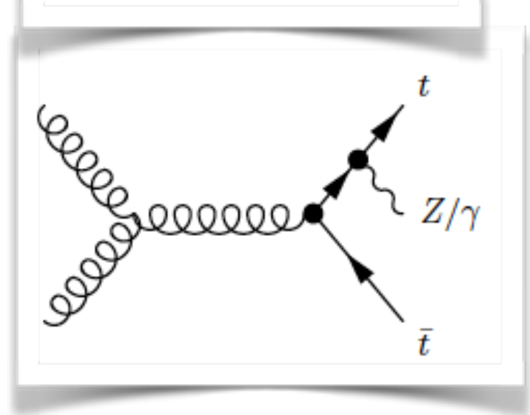
$$O_{\varphi tb} = i(\varphi^\dagger D_\mu\varphi)(\bar{t}\gamma^\mu b)$$

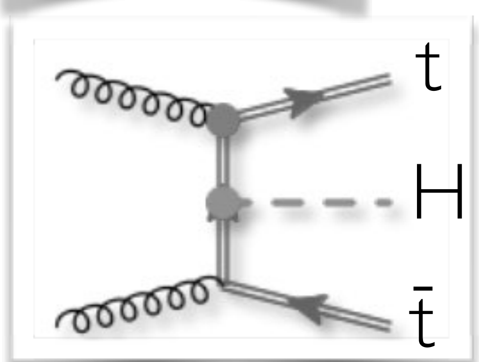
$$O_G = g_s f^{ABC} G^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$$

$$O_{\varphi G} = g_s^2\,(\varphi^\dagger\varphi)\,G^A_{\mu\nu}G^{A\mu\nu}$$

4-fermion ops







Operators and processes

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

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

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

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

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

$$O_{bW} = y_b g_w(\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu}$$

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

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

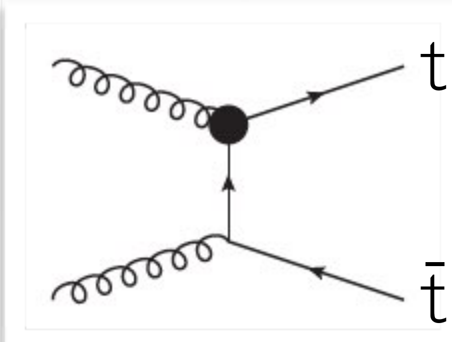
$$O_{t\varphi} = (\varphi^\dagger\varphi)(\bar{Q}t\tilde{\varphi})$$

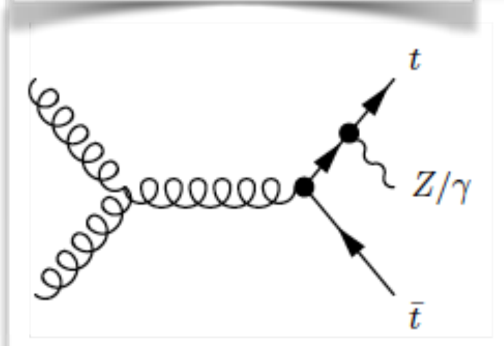
$$O_{\varphi tb} = i(\varphi^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu b)$$

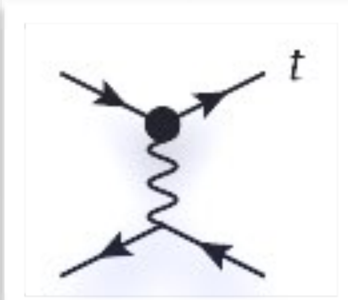
$$O_G = g_s f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$

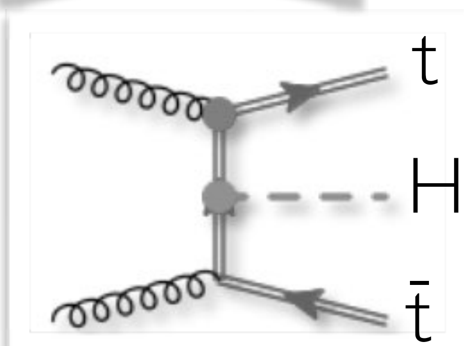
$$O_{\varphi G} = g_s^2\left(\varphi^\dagger\varphi\right)G^A_{\mu\nu}G^{A\mu\nu}$$

4-fermion ops









Operators and processes

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

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

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

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

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

$$O_{bW} = y_b g_w (\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu}$$

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

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

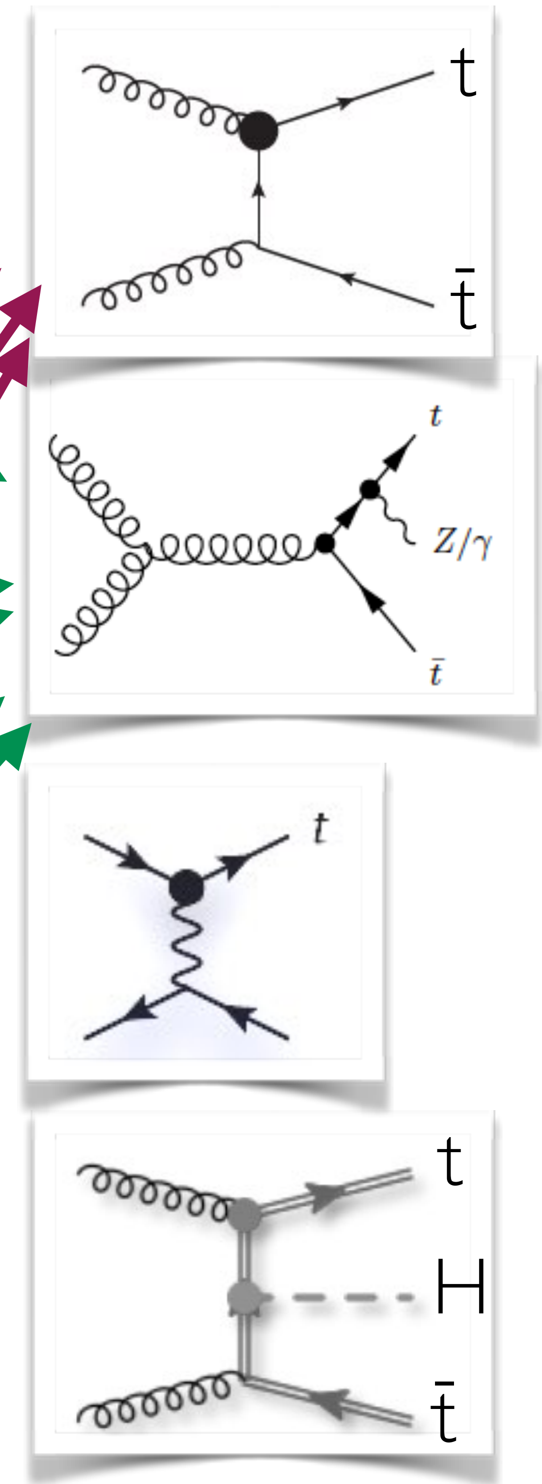
$$O_{t\varphi} = (\varphi^\dagger\varphi)(\bar{Q}t\tilde{\varphi})$$

$$O_{\varphi tb} = i(\varphi^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu b)$$

$$O_G = g_s f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$

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

4-fermion ops



Operators and processes

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

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

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

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

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

$$O_{bW} = y_b g_w (\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu}$$

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

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

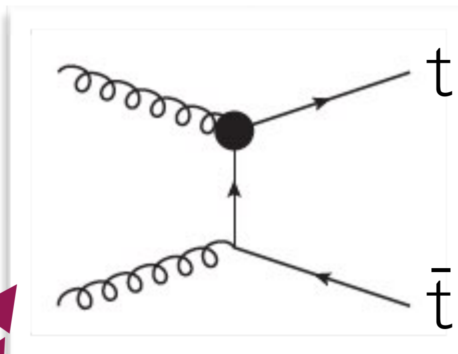
$$O_{t\varphi} = (\varphi^\dagger\varphi)(\bar{Q}t\tilde{\varphi})$$

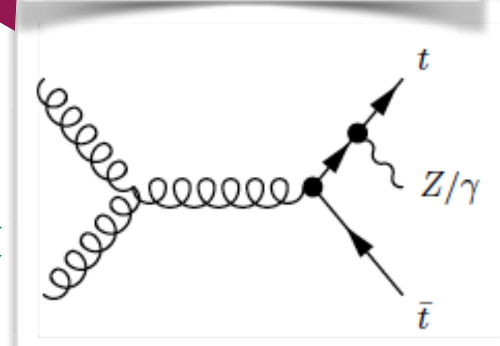
$$O_{\varphi tb} = i(\varphi^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu b)$$

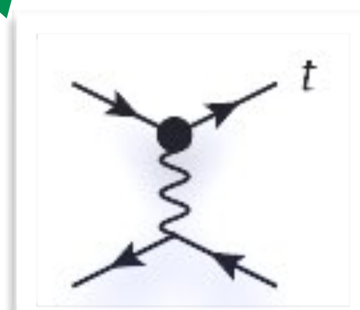
$$O_G = g_s f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$

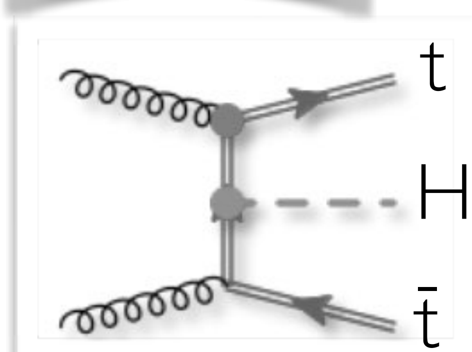
$$O_{\varphi G} = g_s^2 \,(\varphi^\dagger\varphi)\, G^A_{\mu\nu} G^{A\mu\nu}$$

4-fermion ops









Operators and processes

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

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

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

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

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

$$O_{bW} = y_b g_w (\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu}$$

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

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

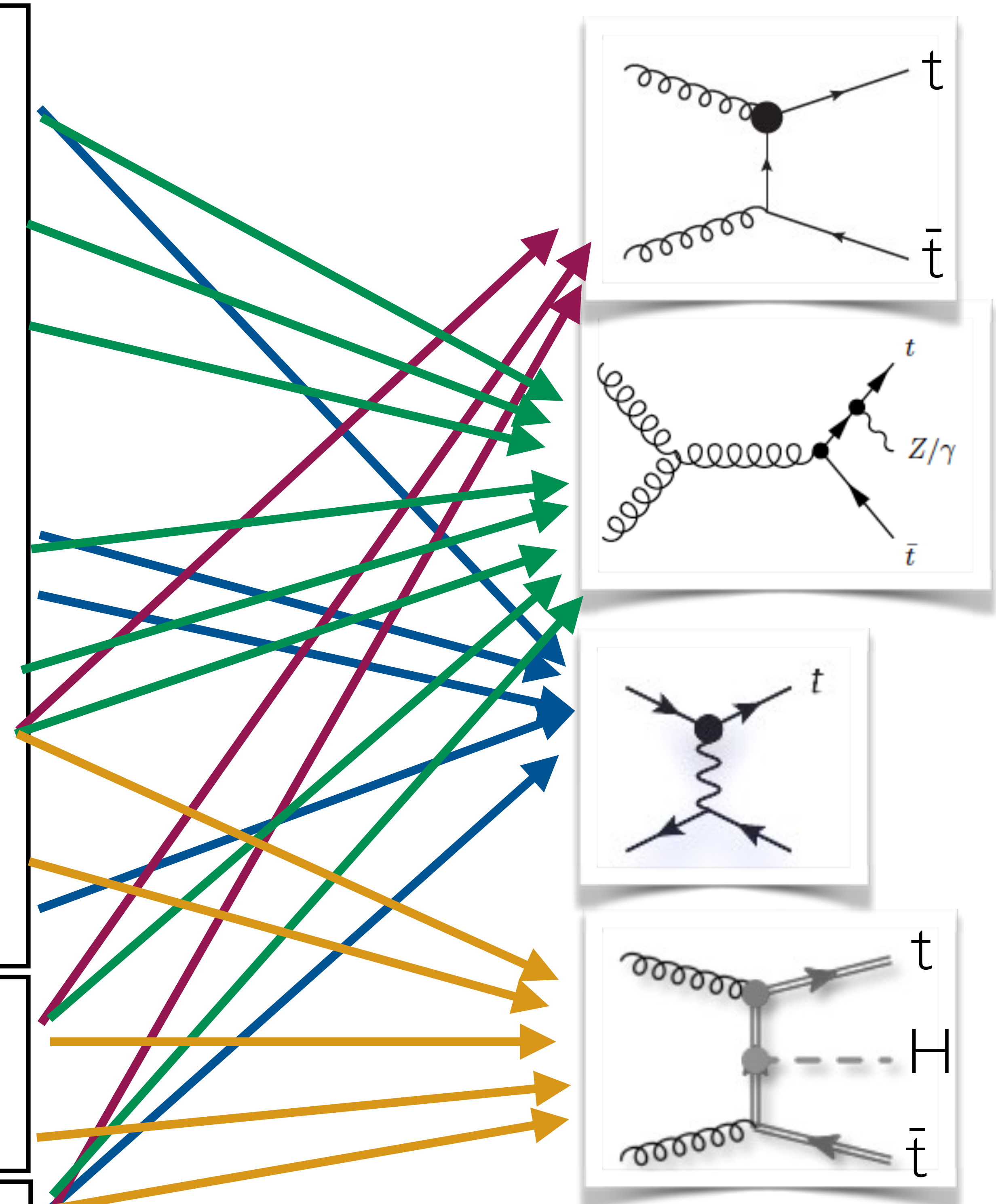
$$O_{t\varphi} = (\varphi^\dagger \varphi)(\bar{Q} t \tilde{\varphi})$$

$$O_{\varphi tb} = i(\varphi^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu b)$$

$$O_G = g_s f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$

$$O_{\varphi G} = g_s^2 (\varphi^\dagger \varphi) G^A_{\mu\nu} G^{A\mu\nu}$$

4-fermion ops



Operators and processes

Several operators typically enter each process at LO (or at LO^2) and also at NLO in QCD (5F, mb=0):

NLO (no 4f)	Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{bW}	$O_{\varphi tb}$	O_{4f}	O_G	$O_{\varphi G}$
✓	$t \to bW \to bl^+\nu$	N		L	L				L^2	L^2	1L^2		
✓	$pp \to tj$	N		L	L				L^2	L^2	1L		
✓	$pp \to tW$	L		L	L				L^2	L^2	1N	N	
✓	$pp \to t\bar{t}$	L									2L-4N	L	
✓	$pp \to t\bar{t}j$	L									2L-4N	L	
✓	$pp \to t\bar{t}\gamma$	L	L	L							2L-4N	L	
✓	$pp \to t\bar{t}Z$	L	L	L	L	L	L				2L-4N	L	
✓	$pp \to t\bar{t}W$	L								L	1L-2L		
✓	$pp \to t\gamma j$	N	L	L	L				L^2	L^2	1L		
✓	$pp \to tZj$	N	L	L	L	L	L		L^2	L^2	1L		
✓	$pp \to t\bar{t}t\bar{t}$	L									2L-4L	L	
✓	$pp \to t\bar{t}H$	L						L			2L-4L	L	L
✓	$pp \to tHj$	N		L	L			L	L^2	L^2	1L		N
O ✗	$gg \to H$	L						L				N	L
O ✗	$gg \to Hj$	L						L				L	L
O ✗	$gg \to HH$	L						L				N	L
O ✗	$gg \to HZ$	L			L	L	L	L				N	L

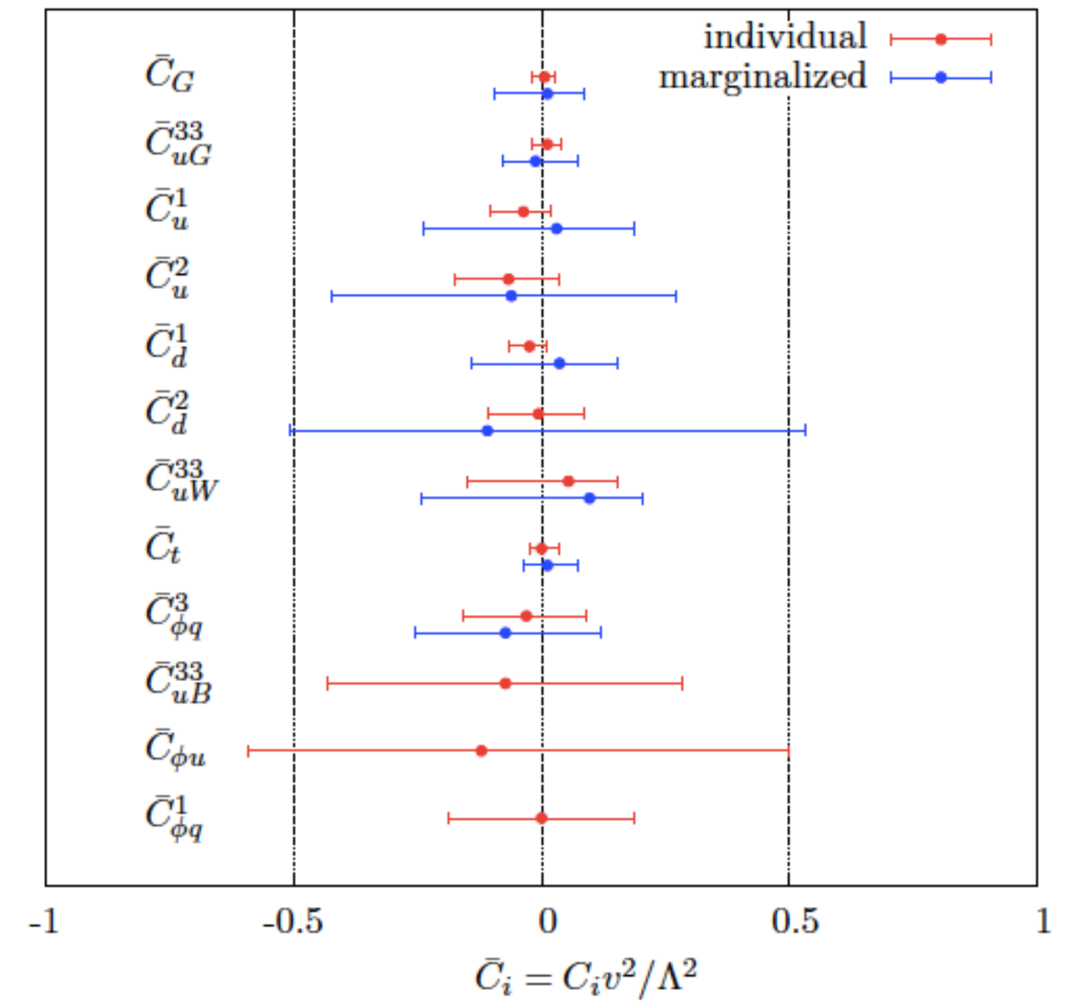
preliminary

Operators and processes : the first fit

[Buckley et al.,2015][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 Tevatron/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).

Operators running and mixing

Operators run and mix under RGE.

Running means that the Wilson coefficients depend on the scale where they are measured (as the couplings in the SM). Note that this introduces also an additional uncertainty in the perturbative computations.

Mixing means that in general the Wilson coefficients at low scale (=where the measurements happen) are related. One immediate consequence is that assumptions about some coefficients being zero at low scales are in general not valid (and in any case have to be consistent with the RGEs). Note also that operator mixing is not symmetric: Op1 can mix into Op2, but not viceversa.

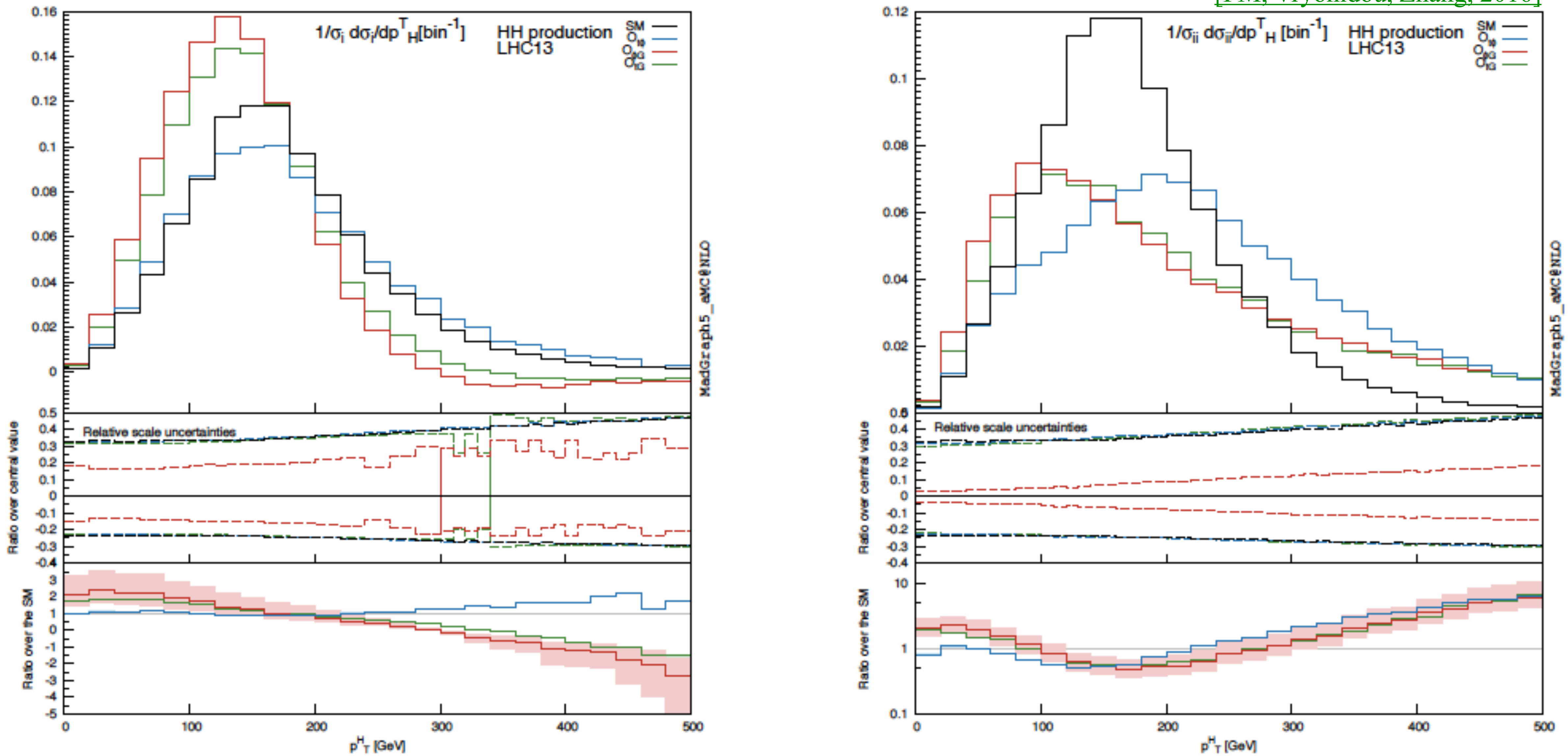
$$\frac{dC_i(\mu)}{d\log\mu} = \frac{\alpha_s}{\pi}\gamma_{ij}C_j(\mu), \qquad \gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix} \qquad (O_{t\phi}, O_{\phi G}, O_{tG})$$

TopEFT : Cui prodest?

- The most appealing feature of the EFT is that bounds on the operators can come from any observable (EWPO, LEP, pp colliders, flavours) and consistently combined.
- Predictions can be systematically improved by including higher-order corrections (in QCD, EW, EFT itself) and match those of the SM dim=4 $\Rightarrow$ increased reach in Λ.
- This comes at the price that one cannot think in terms of one-process and/or one-coupling at the time. A global strategy has to be employed.
- In any case, it is unavoidable if we want to look for new physics not only in the top-quark sector but also in the Higgs interactions.

TopEFT : Cui prodest?

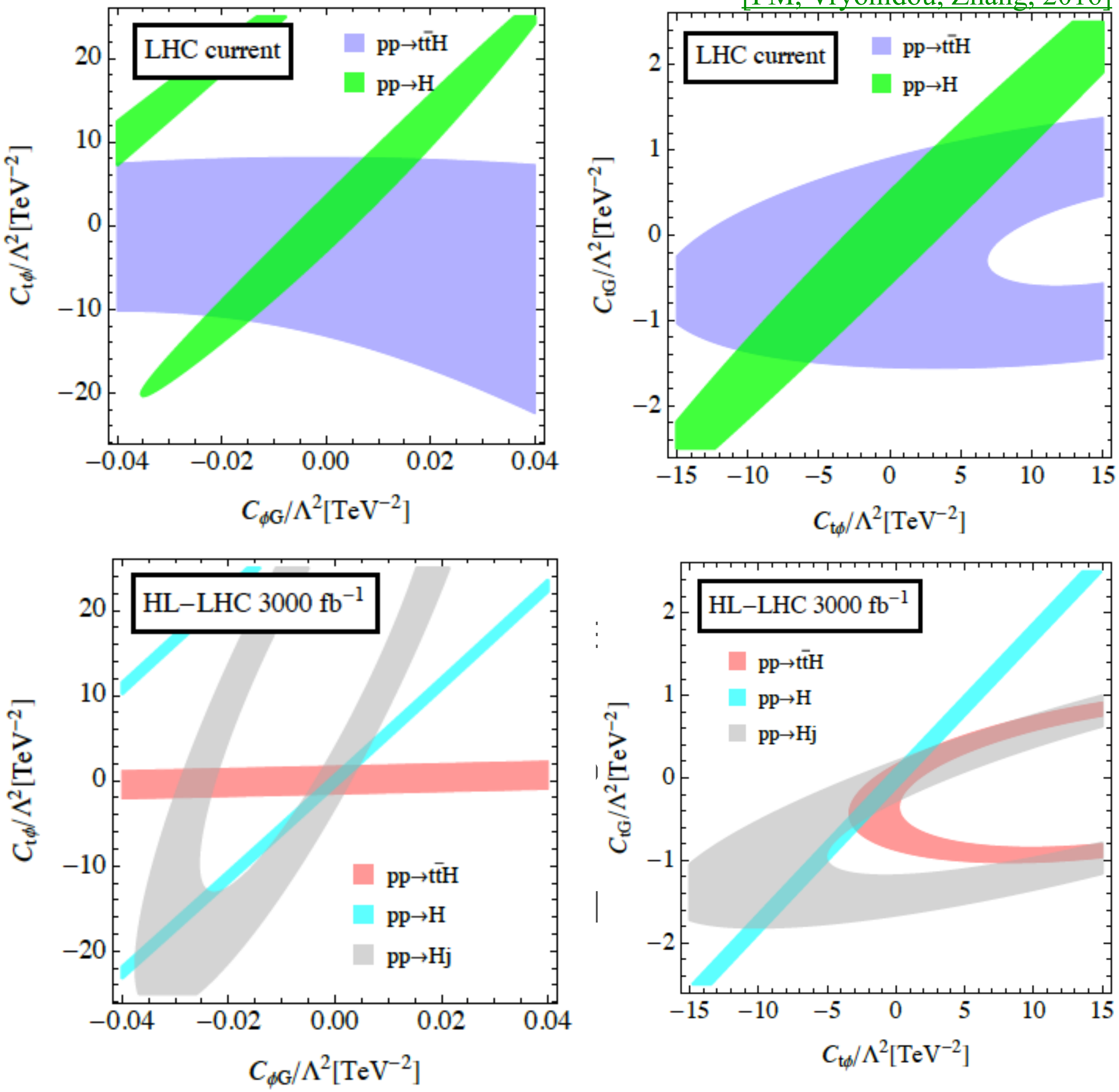
[FM, Vryonidou, Zhang, 2016]



Extracting information on the trilinear HHH couplings from gg>HH will crucially depend on our ability to independently constrain $(O_{t\phi}, O_{\phi G}, O_{tG})$.

TopEFT : Cui prodest?

[FM, Vryonidou, Zhang, 2016]



Current limits using LHC measurements

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

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

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

14TeV projection

3000 fb-1

TopEFT : implementation

Several technical aspects enter in an EFT fit:

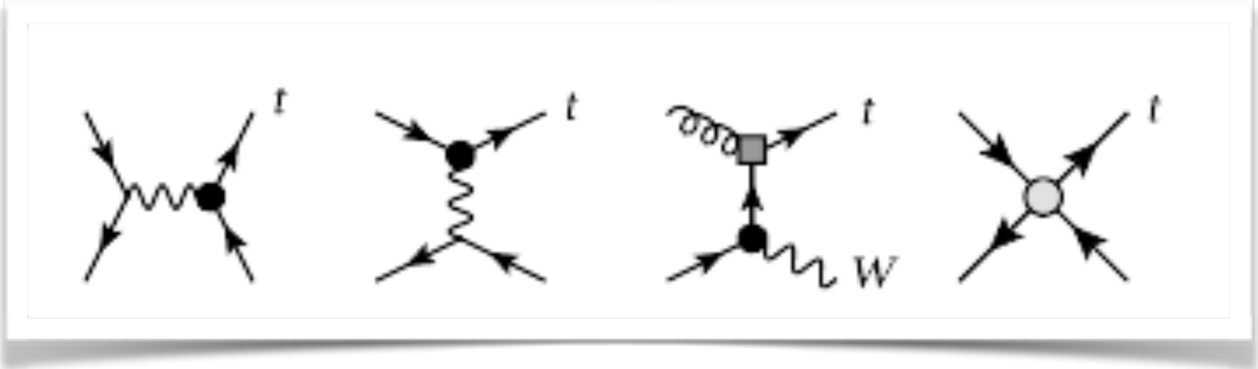
- Choices of global/discrete symmetries: flavour, CP, FCNC,…
- Simplifying assumptions or UV-biases (strong/weak UV completion).
- Estimation of the TH uncertainties (PDF, ren/fact scale, EFT scales, dim=8)
- Study of scaling/behaviour of the $1/\Lambda^2$ vs $1/\Lambda^4$ contributions
  - Square > interference possible in a SI scenario even when $E<\Lambda$.
  - Accidental cancellations of the interference $1/\Lambda^2$ due to helicity mismatch
  - SM amplitude is suppressed (or zero) (Ex: FCNC)
  - Enhancement of operators scaling like v^2/Λ^2 due to unitarity non-cancellations.
- Require the EFT expansion to be valid ($E<\Lambda$), include the quadratic (squares and cross terms) contributions in the central value and consider them in the estimate of the uncertainties. Report limits as a function of the max scale probed in the process [Contino et al., 2016] .

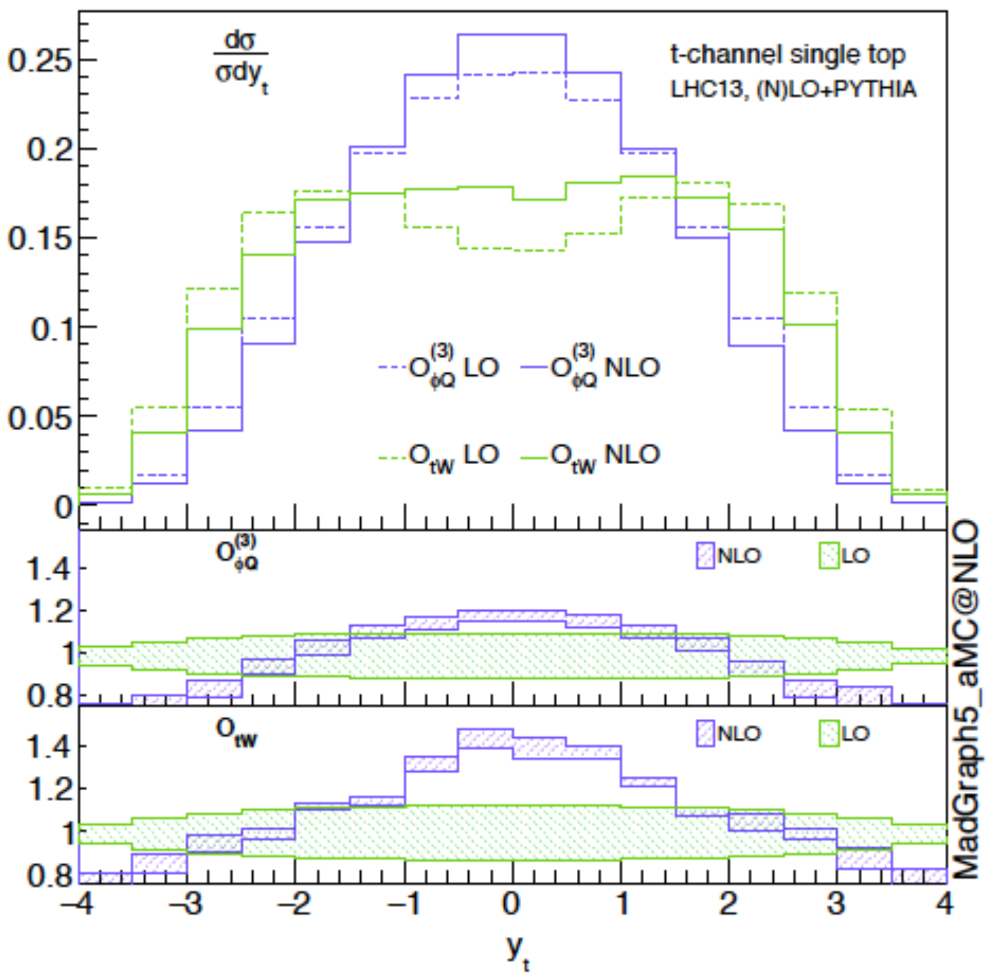
TopEFT at NLO in QCD

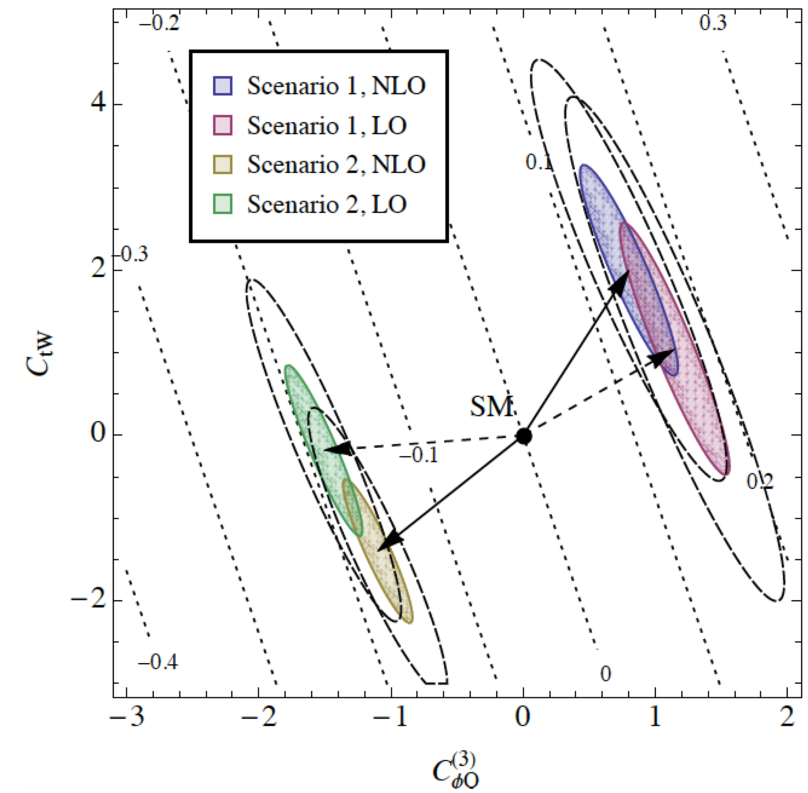
- Extracting information from hadron measurements implies the need for sufficiently accurate and precise EFT predictions.
- In order to correctly estimate the central values and the uncertainties the minimal meaningful order in PT is NLO.
- New operators might contribute to processes at NLO.
- The structure of the EFT becomes non-trivial at NLO and EFT uncertainties can only be reliably estimated starting at NLO.
- Scale uncertainties at LO are large and NLO in QCD corrections turn out to be large.

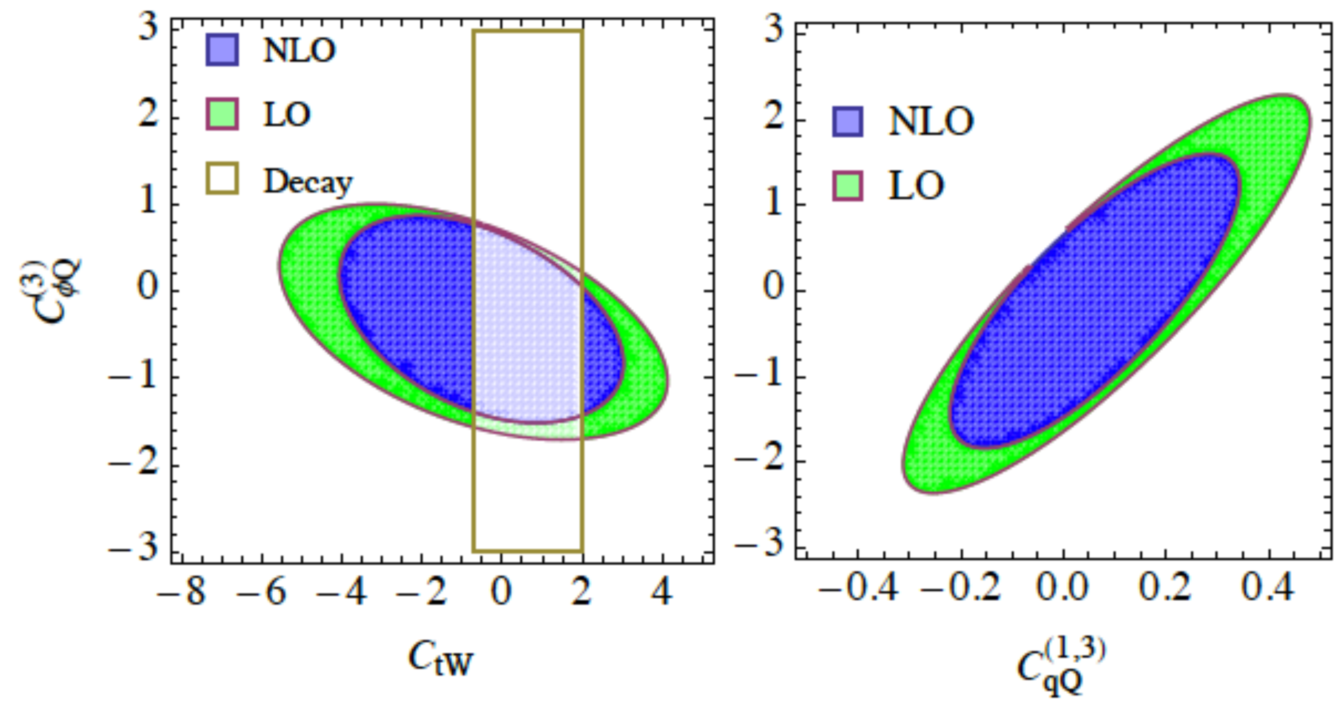
TopEFT at NLO in QCD

[Cen Zhang, 2016]



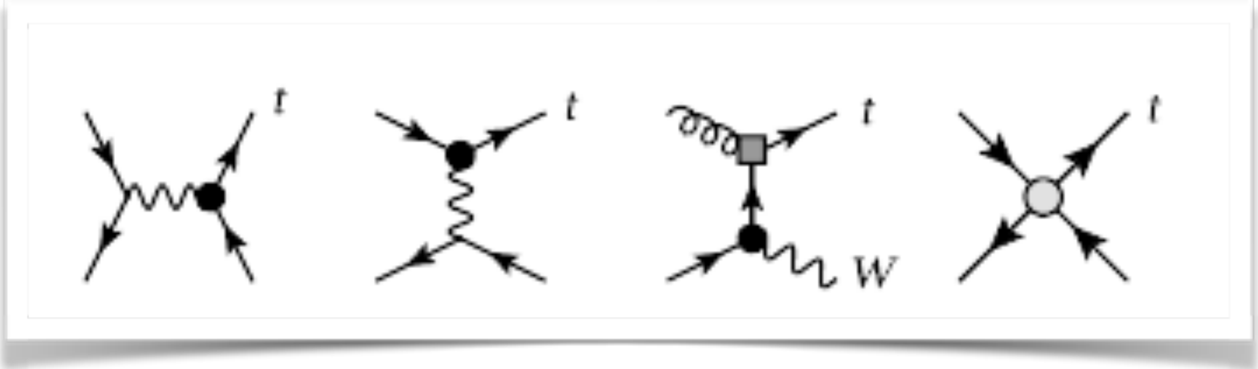


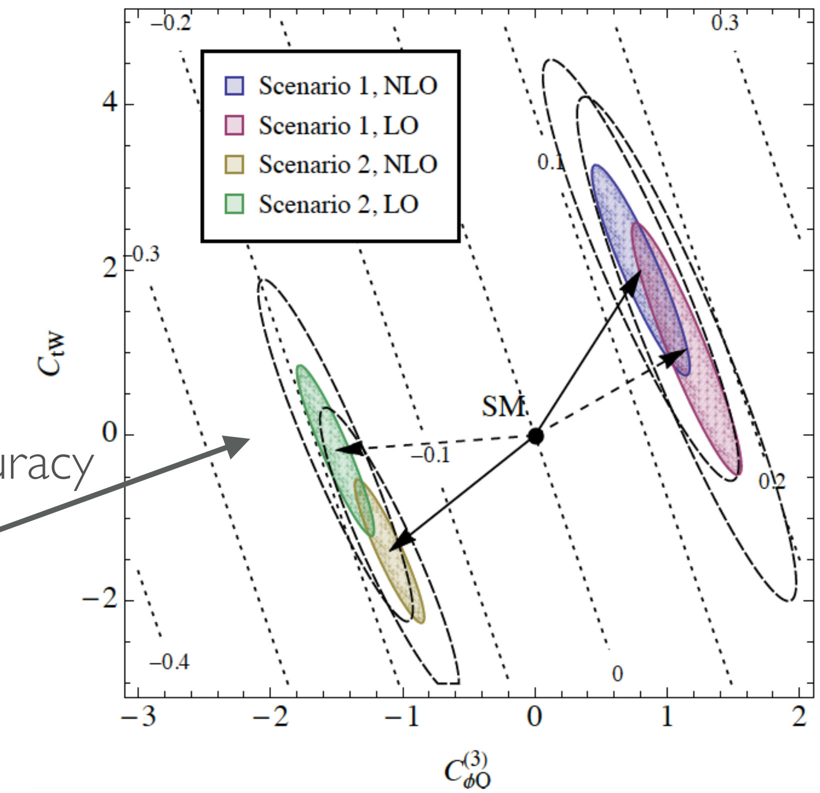




TopEFT at NLO in QCD

[Cen Zhang, 2016]



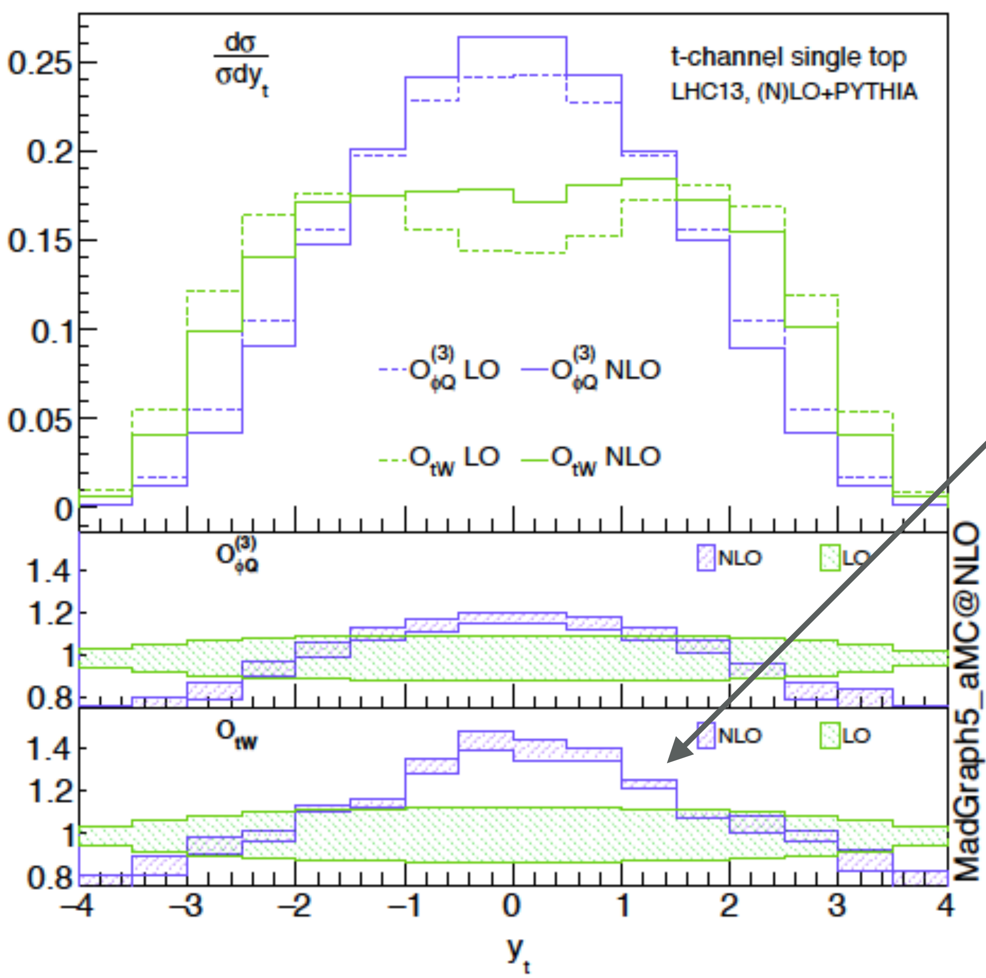


accuracy

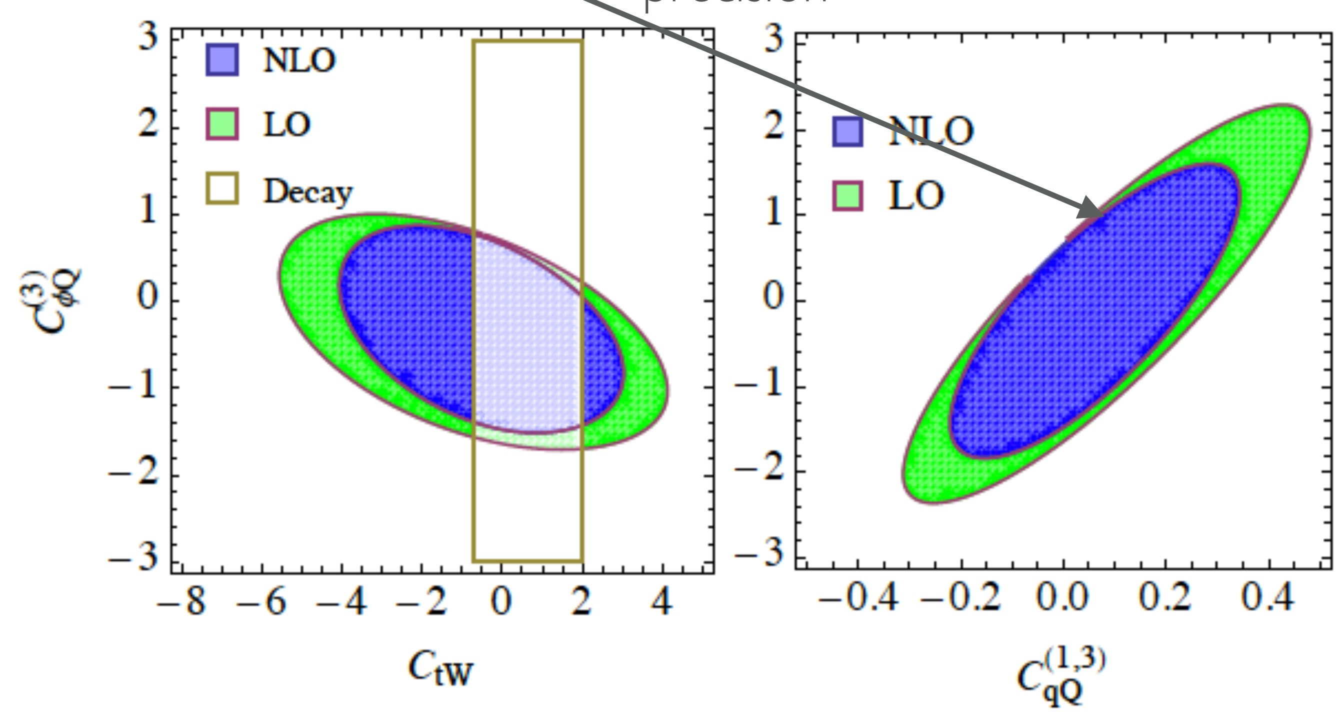
non negligible

NLO effects

precision



shapes (≠from NLO SM)



TopEFT: running and mixing

As first example, let us consider the uncertainties associated to changes of μ_{EFT} . The result at μ_0 can be expressed as:

$$\sigma(\mu_0) = \sigma_{SM} + \sum_i \frac{1\text{TeV}^2}{\Lambda^2} C_i(\mu_0)\sigma_i(\mu_0) + \sum_{i,j} \frac{1\text{TeV}^4}{\Lambda^4} C_i(\mu_0)C_j(\mu_0)\sigma_{ij}(\mu_0)\,,$$

While the same result at a different scale μ can be expressed as:

$$\begin{aligned}\sigma(\mu) =& \sigma_{SM} + \sum_i \frac{1\text{TeV}^2}{\Lambda^2} C_i(\mu)\sigma_i(\mu) + \sum_{i,j} \frac{1\text{TeV}^4}{\Lambda^4} C_i(\mu)C_j(\mu)\sigma_{ij}(\mu) \\ =& \sigma_{SM} + \sum_i \frac{1\text{TeV}^2}{\Lambda^2} C_i(\mu_0)\sigma_i(\mu_0;\mu) + \sum_{i,j} \frac{1\text{TeV}^4}{\Lambda^4} C_i(\mu_0)C_j(\mu_0)\sigma_{ij}(\mu_0;\mu)\end{aligned}$$

with:

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

$$\sigma_i(\mu_0;\mu) = \Gamma_{ji}(\mu,\mu_0)\sigma_j(\mu)\,,$$

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

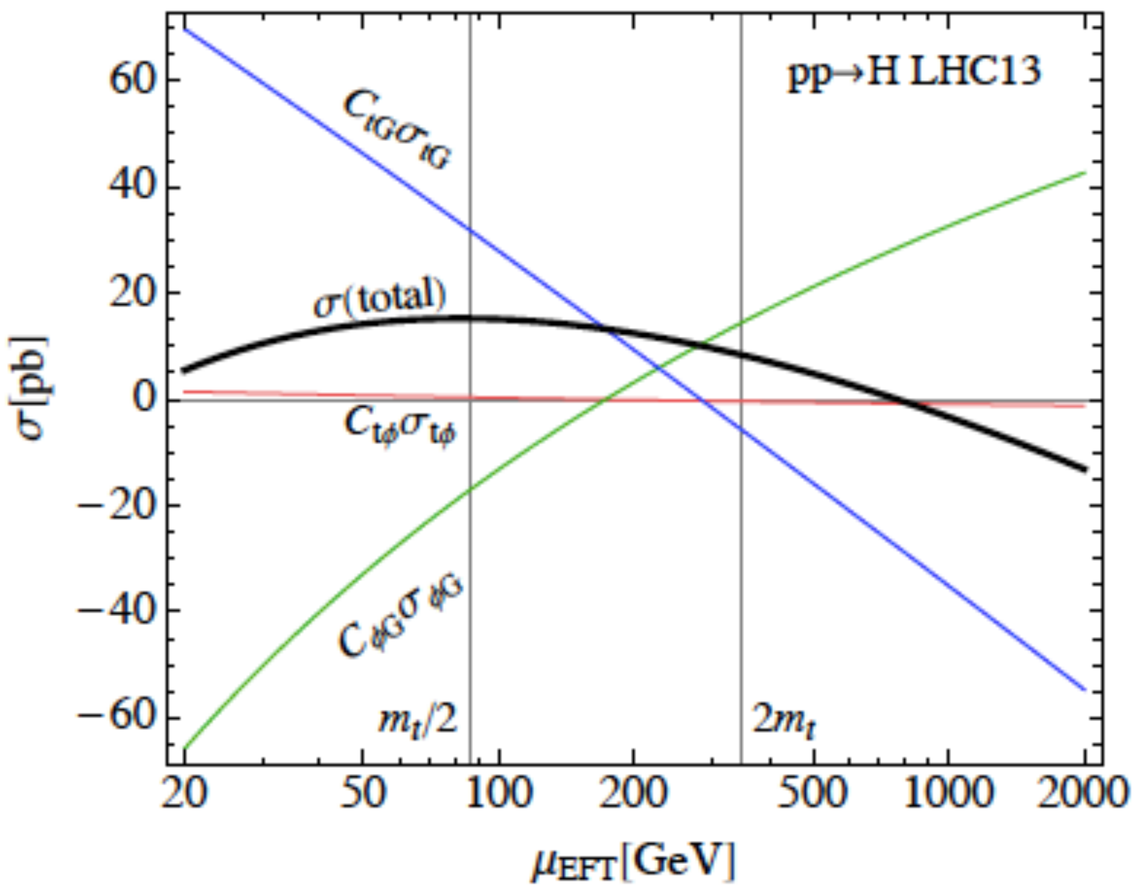
$$\Gamma_{ij}(\mu,\mu_0) = \exp\left(\frac{-2}{\beta_0}\log\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\gamma_{ij}\right)$$

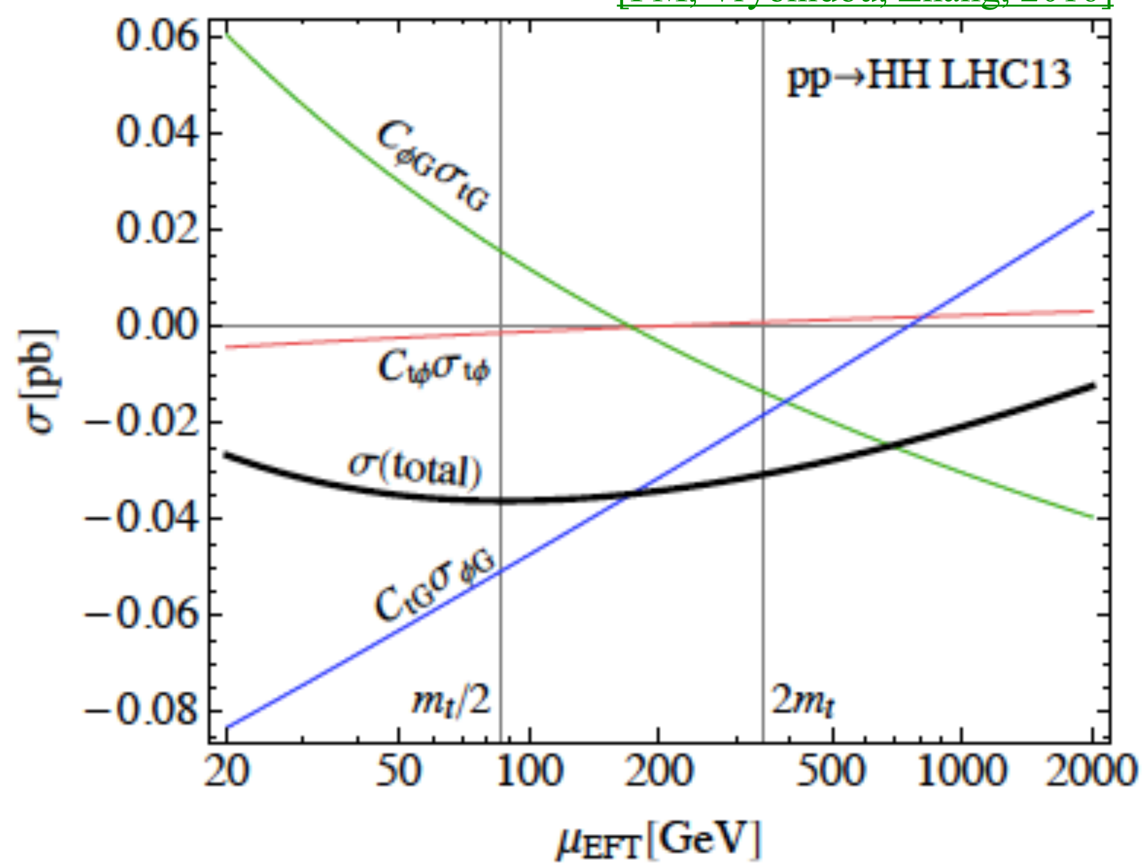
$$\beta_0 = 11 - 2/3n_f\,,$$

TopEFT: running and mixing

We can now vary μ_{EFT} to estimate the residual uncertainties. Consider H and HH production via $(O_{t\phi}, O_{\phi G}, O_{tG})$:

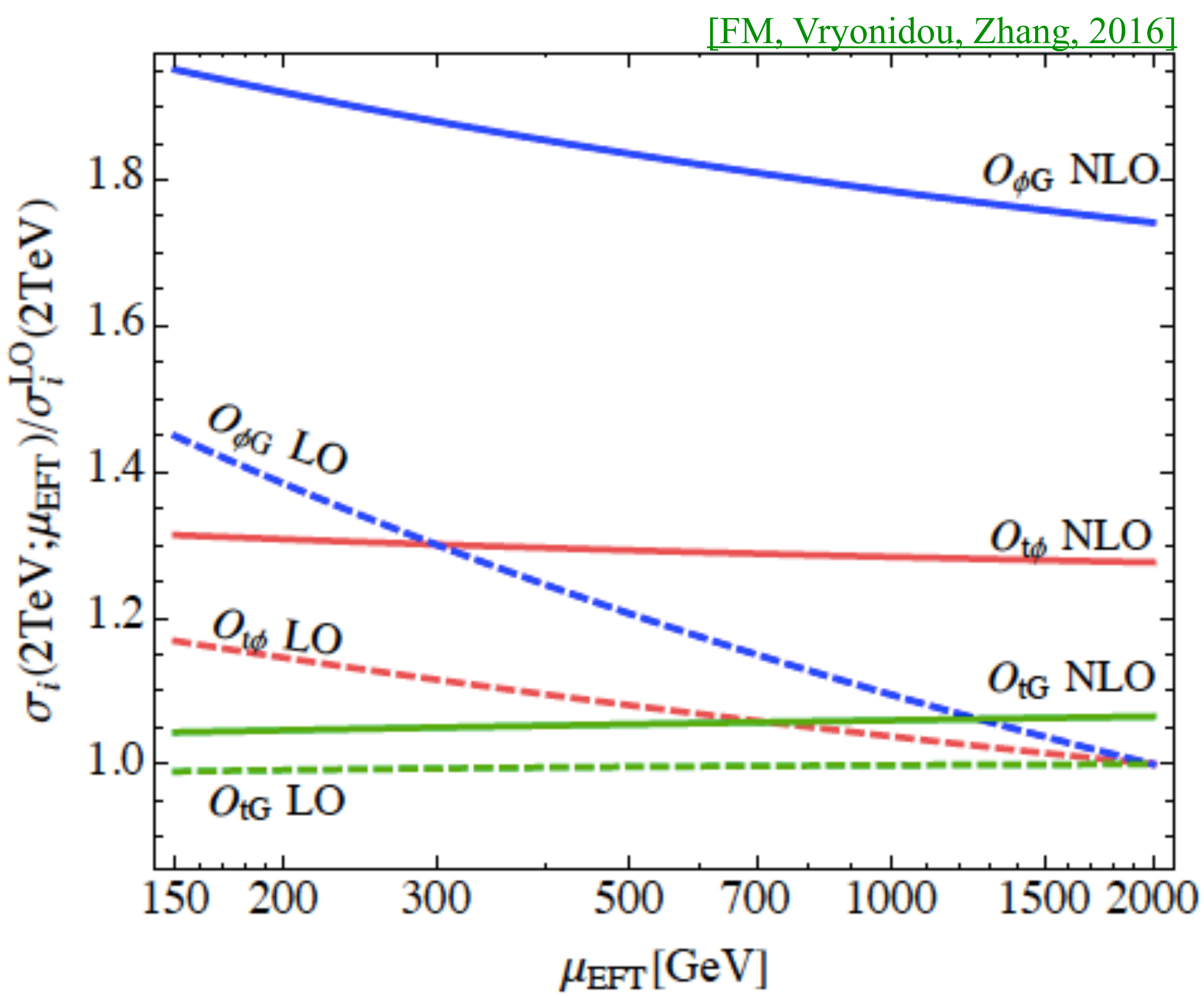
[FM, Vryonidou, Zhang, 2016]





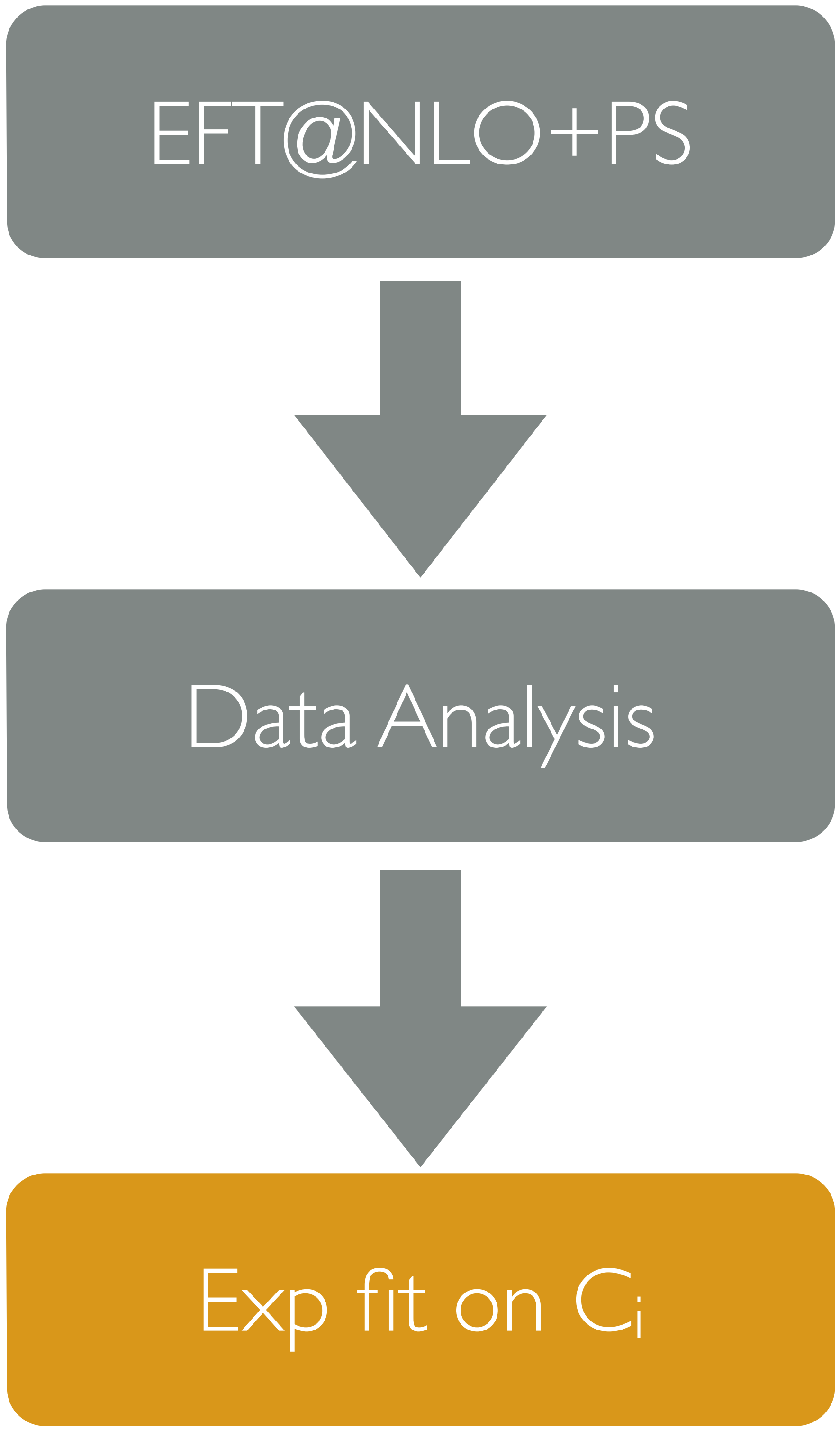
By including the mixing, the overall scale dependence at LO, is very much reduced with respect to the single ones.

TopEFT : RG vs NLO



- Consider the RG and NLO effects in ttH.
- Take an EFT matched to a full theory at 2 TeV.
- Compute the σ_i at LO with μ_{EFT}=2 TeV.
- Improve the results by running down to $\mu_{EFT} \sim m_t$. σ_i increase by 50%.
- The estimates obtained through the RG running are substantially off wrt the exact NLO computations.

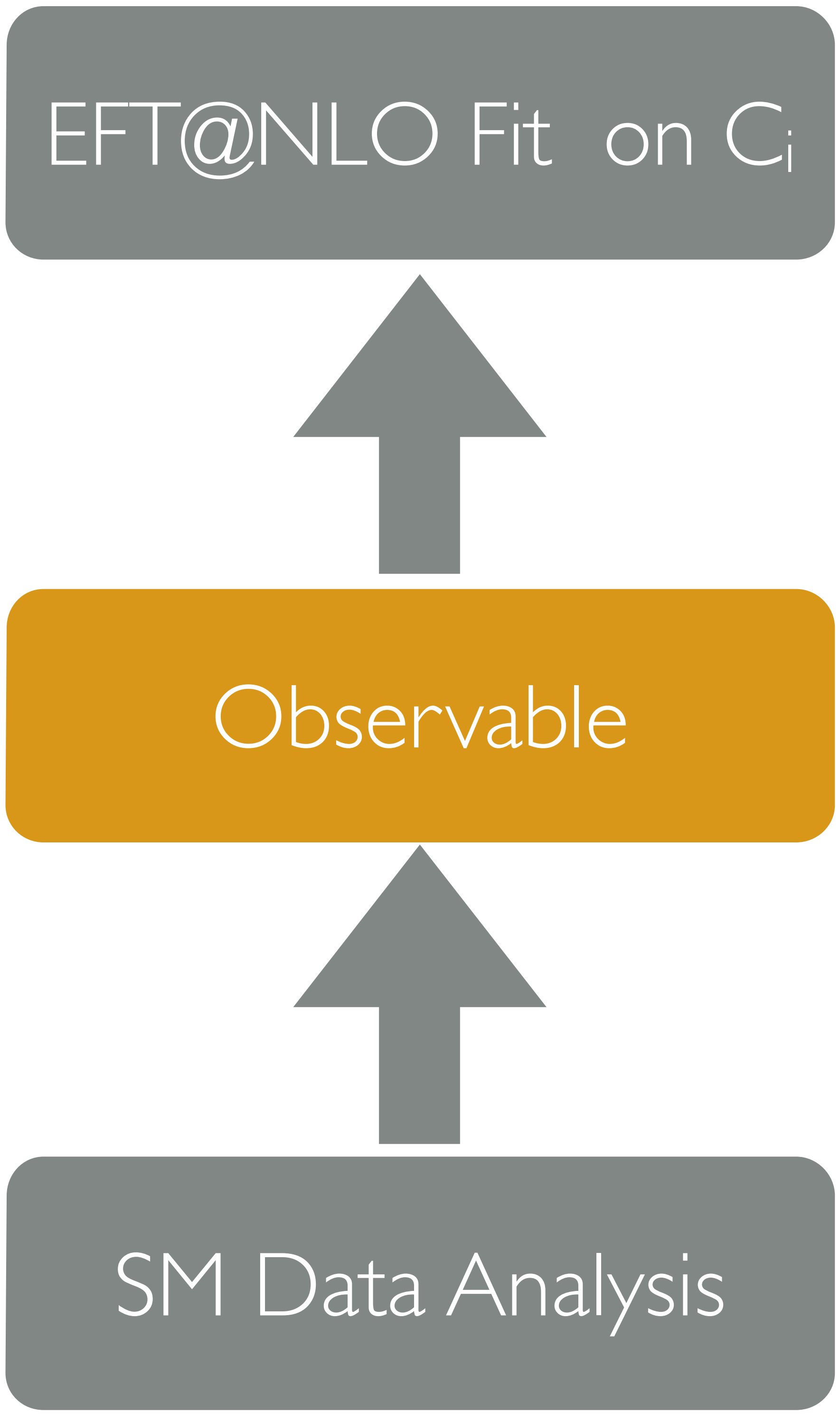
How to proceed?



OPTION top-down

- This is the ideal way as it would maximise the sensitivity (in analogy to any BSM top-down search) and it does not need providing information back at the particle level.
- However, it assumes several important conditions:
  - The analyses at the experimental level are fully coordinated and can be combined.
  - The theoretical setup is final and the dependence on additional theoretical assumptions is minimal.
- While globally this might not be a realistic option, feasibility studies could start for specific subsets.

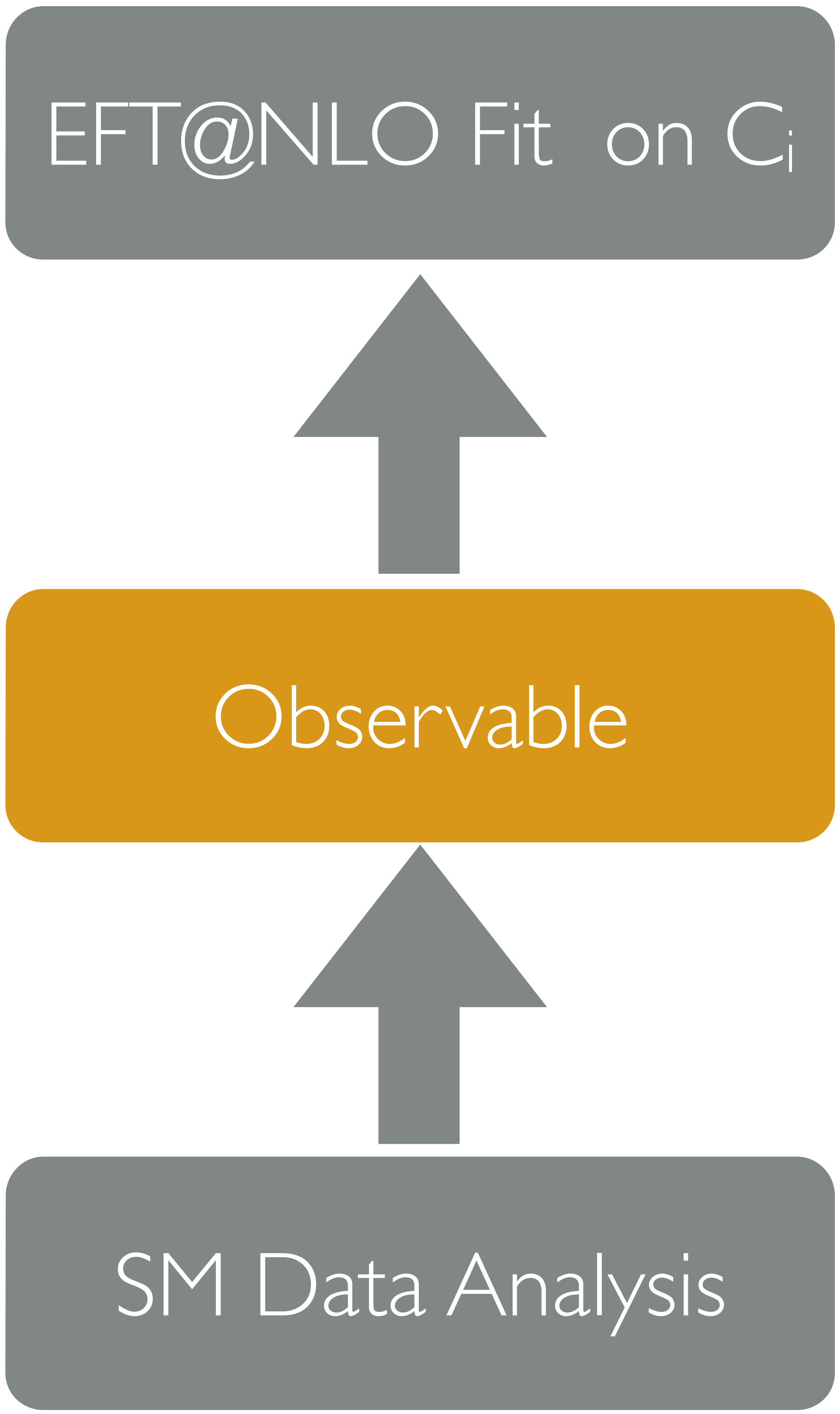
How to proceed?



OPTION bottom-up

- A (continuously extendable) set of observables is identified and measured.
- Such observables can be of various types, from "total cross section" to differential distributions, typically at the particle level.
- Ex: total cross sections, pt(top), eta(top), pt(tt), delta_phi(leptons), A_C, polarisation fractions, spin correlation matrix,…
- Results are provided with the minimal systematic uncertainty breakdown so that they can be combined with other measurements.
- One dimensional differential distributions should be provided with the bin-by-bin correlation matrix.

How to proceed?



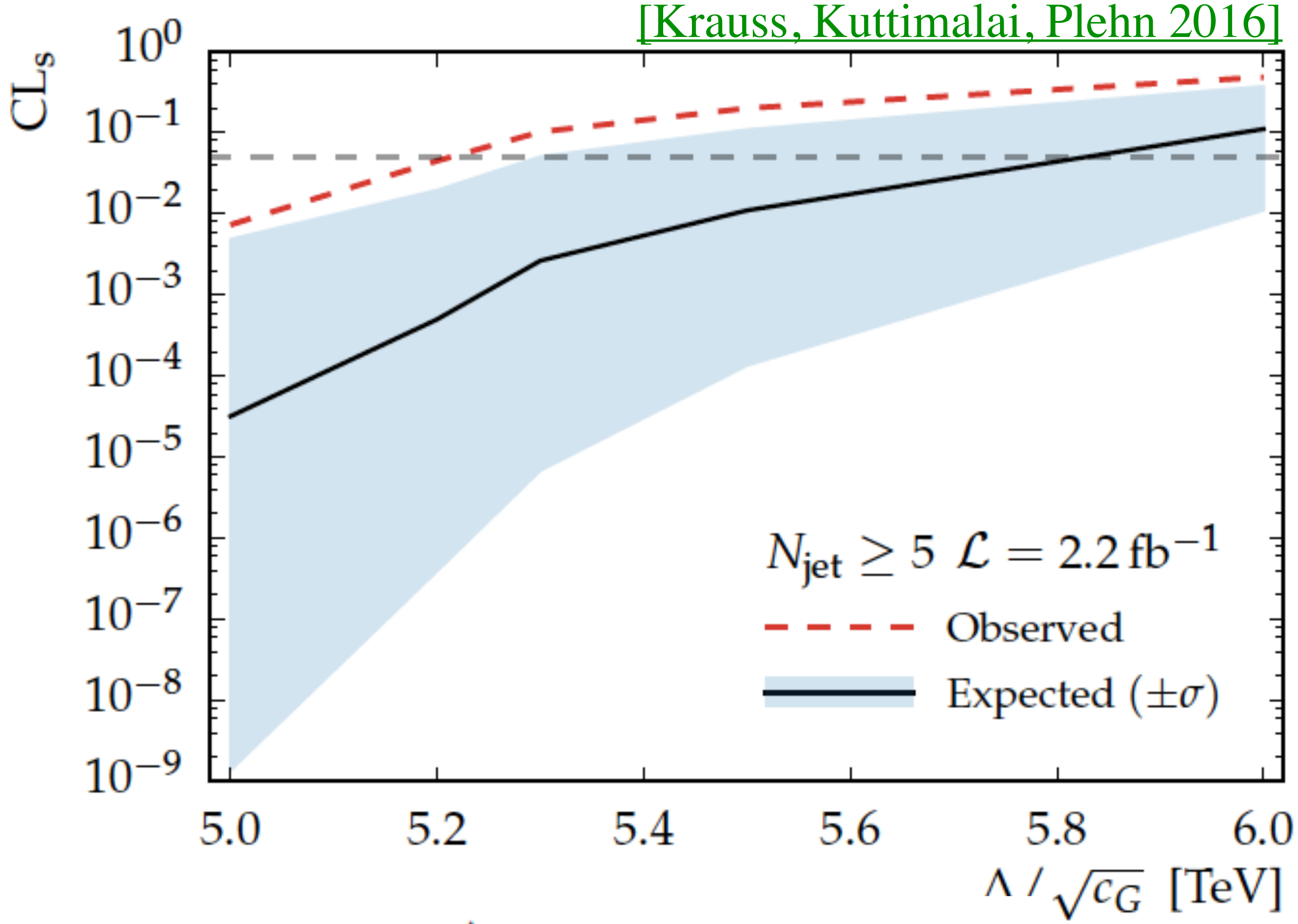
OPTION bottom-up

- This approach has the advantage that TH predictions, evaluations of the uncertainties, constraints coming from other studies, can be constantly and continuously included (see EXAMPLE).
- It could be used to prepare a top-down and global approach.
- It might motivate and pave the way to the more sensitive EXP fits.

Example

$$O_G = g_s f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$$

[Krauss, Kuttimalai, Plehn 2016]



$$\frac{\Lambda}{\sqrt{c_G}} > 5.2 \text{ TeV} \qquad \text{(observed)}$$

$$\frac{\Lambda}{\sqrt{c_G}} > 5.8 \text{ TeV} \qquad \text{(expected)}$$

- This operator enters at LO all ttbar +X production channels.
- It contributes to gg → gg only via the square (interference is zero, see [Dixon and Shadmi, 1993], [Azatov et al. 2016]
- Until now it has been swept under the carpet…(thought to be possible to bound it with di-jets).
- In fact, the multi-jet data at 13 TeV can constrain this operator extremely efficiently.

Which observables?

Process	$\sigma_{\mathrm{NLO+}}$ at 13 TeV
$pp \to t\bar{t}$	830 pb
$pp \to t\bar{t}j$	410 pb
$pp \to tj$	221 pb
$pp \to t\bar{t}jj$	179 pb
$pp \to tW$	71 pb
$pp \to t\bar{t}\gamma$	2750 fb
$pp \to t\gamma j$	1010 fb
$pp \to t\bar{t}Z$	873 fb
$pp \to tZj$	699 fb
$pp \to t\bar{t}W$	644 fb
$pp \to t\bar{t}t\bar{t}$	13.3 fb
$pp \to t\bar{t}H$	507 fb
$gg \to H$	48.5 pb
$gg \to Hj$	14 pb
$gg \to Hjj$	5 pb
$gg \to HZ$	140 fb
$pp \to tHj$	74 fb
$gg \to HH$	33.5 fb

pt(j)>30 GeV, pt(gamma)>20 GeV

Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{bW}	$O_{\varphi tb}$	O_{4f}	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	N		L	L				L^2	L^2	$1L^2$		
$pp \to tj$	N		L	L				L^2	L^2	1L		
$pp \to tW$	L		L	L				L^2	L^2	1N	N	
$pp \to t\bar{t}$	L									2L-4N	L	
$pp \to t\bar{t}j$	L									2L-4N	L	
$pp \to t\bar{t}\gamma$	L	L	L							2L-4N	L	
$pp \to t\bar{t}Z$	L	L	L	L	L	L				2L-4N	L	
$pp \to t\bar{t}W$	L								L	1L-2L		
$pp \to t\gamma j$	N	L	L	L				L^2	L^2	1L		
$pp \to tZj$	N	L	L	L	L	L		L^2	L^2	1L		
$pp \to t\bar{t}t\bar{t}$	L									2L-4L	L	
$pp \to t\bar{t}H$	L						L			2L-4L	L	L
$pp \to tHj$	N		L	L			L	L^2	L^2	1L		N
$gg \to H$	L						L				N	L
$gg \to Hj$	L						L				L	L
$gg \to HH$	L						L				N	L
$gg \to HZ$	L			L	L	L	L				N	L

Collider variables:

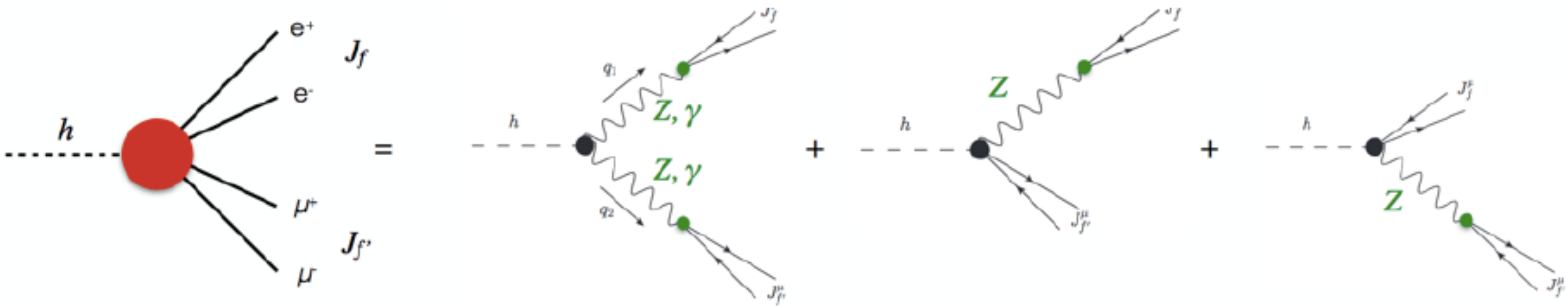
- σ_{TOT}
- $p_T(t)$, $\eta(t)$, $m(tt)$
- pt(l), η(l), m(ll), Δphi(l,l), …
- spin correlations 15 coefficients [Bernreuther, 2016] [ATLAS, 2016]
- W helicities
- $p_T(B)$, $\eta(B)$, $B=\gamma,Z,W,H$.
- Asymmetries: A_C, …

+ LEP, EWPO, Flavor…

Summary

- In an EFT bounds on the operators coming from any observable (EWPO, LEP, pp colliders, flavours) can be consistently combined. Predictions can be systematically improved by including higher-order corrections (in QCD, EW, EFT itself) to match those of the SM dim=4.
- NLO(+PS) results are needed to gain the sufficient control of uncertainties and are now available for a wide range of processes and operators. The main ingredient to be completed are 4F interactions. Tools available for experimentalists.
- Top-down and bottom-up approaches are both possible. Identification of the key observables and the best TH/EXP communication strategy should be discussed.

Pseudo-observables in Higgs decay



$$\mathcal{T}^{\mu\nu}_{n.c.}(q_1,q_2) = \left[F_L^{ff'}(q_1^2,q_2^2)g^{\mu\nu} + F_T^{ff'}(q_1^2,q_2^2)\frac{q_1\cdot q_2\, g^{\mu\nu} - q_2{}^{\mu} q_1{}^{\nu}}{m_Z^2} + F_{CP}^{ff'}(q_1^2,q_2^2)\frac{\varepsilon^{\mu\nu\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

$$F_L^{ff'}(q_1^2,q_2^2) = \kappa_{ZZ}\frac{g_Z^f g_Z^{f'}}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Zf}}{m_Z^2}\frac{g_Z^{f'}}{P_Z(q_2^2)} + \frac{\epsilon_{Zf'}}{m_Z^2}\frac{g_Z^f}{P_Z(q_1^2)} + \Delta_L^{\rm SM}(q_1^2,q_2^2)\,,$$

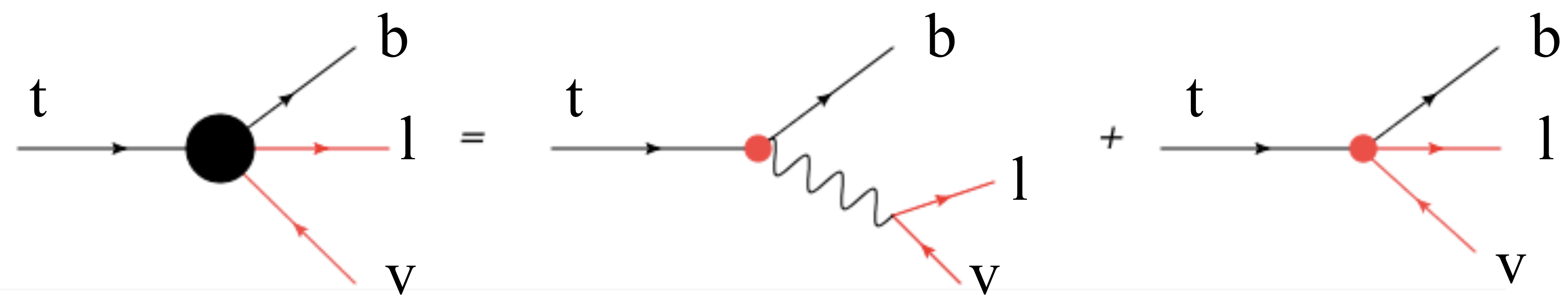
$$F_T^{ff'}(q_1^2,q_2^2) = \epsilon_{ZZ}\frac{g_Z^f g_Z^{f'}}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}\left(\frac{eQ_{f'}g_Z^f}{q_2^2 P_Z(q_1^2)} + \frac{eQ_f g_Z^{f'}}{q_1^2 P_Z(q_2^2)}\right) + \epsilon_{\gamma\gamma}\frac{e^2 Q_f Q_{f'}}{q_1^2 q_2^2}$$
$$+\Delta_T^{\rm SM}(q_1^2,q_2^2),$$

$$\Gamma(h\to Z_L Z_L) \equiv \frac{\Gamma(h\to 2e2\mu)[\kappa_{ZZ}]}{\mathcal{B}(Z\to 2e)\mathcal{B}(Z\to 2\mu)} = 0.209\,|\kappa_{ZZ}|^2\ \text{MeV}$$

$$\Gamma(h\to Z_T Z_T) \equiv \frac{\Gamma(h\to 2e2\mu)[\epsilon_{ZZ}]}{\mathcal{B}(Z\to 2e)\mathcal{B}(Z\to 2\mu)} = 0.0189\,|\epsilon_{ZZ}|^2\ \text{MeV}$$

[JAG et Bernabeu, 2010]
[Cen Zhang, 2014]
[JAG et Bernabeu, 2015]

Pseudo-observables in top decay



$$= -\sum_{i=+,0,-} M_\mu^{(bW)}(Q^2)\epsilon_i^{\mu *}\epsilon_i^{\nu} \quad \frac{g}{\sqrt{2}}\bar{\nu}(k_1)\gamma_\nu P_L e(k_2) D(Q^2, m_W, \Gamma_W)^{-1} + \sum_i \bar{\nu}(k_1) O_i e(k_2) \cdot \bar{b}(p_2) O_i t(p_1)$$

↓

$$-\frac{g}{\sqrt{2}}\bar{b}\,\gamma^\mu\,(V_L P_L + V_R P_R)\,t - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_\nu}{M_W}\,(g_L P_L + g_R P_R)\,t$$

The helicity fractions can be used as the simplest physical PO's :

$$\frac{d\Gamma_{be^+\nu}}{dQ^2\, d\cos\theta} = \frac{Q^2}{16\pi^2}\frac{g^2}{2}|D(Q^2, m_W, \Gamma_W)|^{-2}\times$$
$$\left[\Gamma_{bW}^{(+)} f_+(\cos\theta) + \Gamma_{bW}^{(0)} f_0(\cos\theta) + \Gamma_{bW}^{(-)} f_-(\cos\theta)\right]$$

R 0 L

$$f_+(\cos\theta) = \frac{1}{4}(1+\cos\theta)^2$$
$$f_0(\cos\theta) = \frac{1}{2}\sin^2\theta$$
$$f_-(\cos\theta) = \frac{1}{4}(1-\cos\theta)^2$$

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