Learning to pinpoint effective operators at the LHC: a study of the $t\bar{t}b\bar{b}$ signature

Jorgen D'Hondt[(a)], Alberto Mariotti[(a,b)], Ken Mimasu[(c)],
Seth Moortgat[(a)], Cen Zhang [(d)]

(a) Vrije Universiteit Brussel – Interuniversity Institute for High Energies (IIHE)
Pleinlaan 2, B-1050 Brussels, Belgium

(b) Vrije Universiteit Brussel, Theoretische Natuurkunde
Pleinlaan 2, B-1050 Brussels, Belgium

(c) Université catholique de Louvain – Centre for Cosmology, Particle Physics and Phenomenology (CP3)
Chemin du Cyclotron 2, B-1348 Louvain-La-Neuve, Belgium

(d) Chinese Academy of Sciences, Institute of High Energy Physics
Beijing 100049, China

ArXiv:	1807.02130

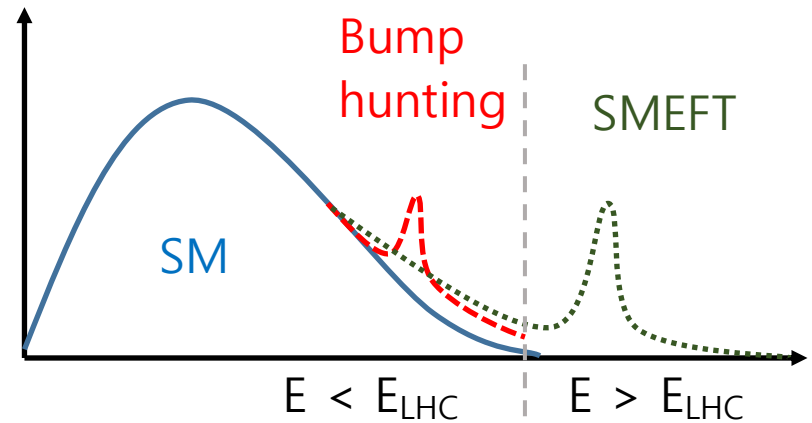
JHEP11(2018)131

HEFT2019 (UCL) – 15th Apr 2019

Contents

1. Introduction: SMEFT

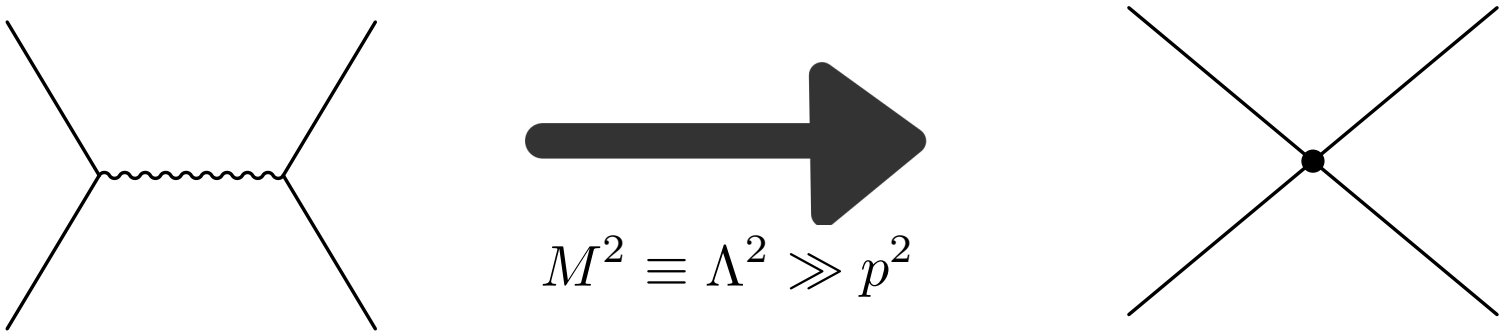
- Lack of direct evidence for BSM physics at the LHC
  → Standard Model Effective Field Theory (SMEFT):
  - model-independent interpretation
  - New physics at high energy scales
  - Heightened energy dependence and modified kinematics



Extend SM Lagrangian up to dim. 6:

(→ Leading B & L conserving contributions)

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



$$M^2 \equiv \Lambda^2 \gg p^2$$

$$\frac{g_*^2}{p^2 - M^2}$$

dim. 6 $$-\frac{g_*^2}{\Lambda^2}\left[1 + \cancel{\frac{p^2}{\Lambda^2}} + \cancel{\frac{p^4}{\Lambda^4}} + \cancel{\cdots}\right]$$

1. Introduction: SMEFT

- Warsaw basis of dim. 6 operators (*B. Grzadkowsk, et al. [JHEP 1010 (2010) 085]*)
- Depending on flavor assumptions, tens to hundreds of independent operators
  → For a given final-state, many simultaneous contributions possible!

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

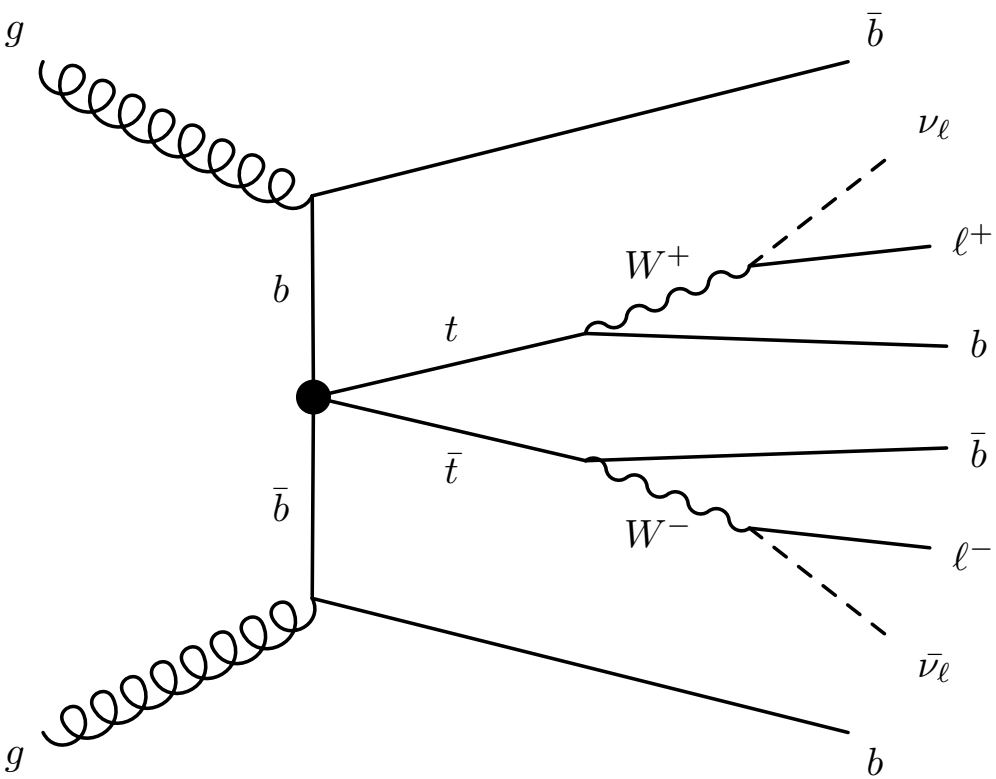
$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$		

	Intrinsically large SMEFT parameter space
×	high-multiplicity final states with complex inter-correlated kinematics
	= multi-class machine learning algorithms

2. $t\bar{t}b\bar{b}$ in SMEFT: four-heavy-quark operators

- $t\bar{t}b\bar{b}$ is sensitive to a set of four-quark dim. 6 operators.
- MFV-inspired approach to separate 4-Heavy, 2-Heavy-2-Light and 4-Light operators
- We focus on 4-Heavy operators
  - 2H2L are constrained much more by $t\bar{t}$ and $b\bar{b}$ production via $q\bar{q}$ initial state



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

2. $t\bar{t}b\bar{b}$ in SMEFT: comparison to four top

- Some operators can be constrained by four top as well

  ex: C. Zhang Chin. Phys.C42(2018), no. 2 023104

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

$$C^{(+)}_{QQ} = \frac{1}{2}C^1_{QQ} + \frac{1}{6}C^8_{QQ}$$

Degeneracy in four-top, lifted for $t\bar{t}b\bar{b}$!

2. $t\bar{t}b\bar{b}$ in SMEFT: comparison to four top

- Some operators can be constrained by four top as well

  ex: C. Zhang Chin. Phys.C42(2018), no. 2 023104

Operator	$t\bar{t}b\bar{b}$	$t\bar{t}t\bar{t}$
$O^1_{QQ} = \frac{1}{2}(\bar{Q}\,\gamma_\mu\,Q)(\bar{Q}\,\gamma^\mu\,Q)$,	✓	✓
$O^8_{QQ} = \frac{1}{2}(\bar{Q}\,\gamma_\mu\,T^A\,Q)(\bar{Q}\,\gamma^\mu\,T^A\,Q)$,	✓	✓
$O^1_{tb} = (\bar{t}\,\gamma_\mu\,t)(\bar{b}\,\gamma_\mu\,b)$,	✓	
$O^8_{tb} = (\bar{t}\,\gamma_\mu T^A\,t)(\bar{b}\,\gamma_\mu\,T^A\,b)$,	✓	
$O^1_{tt} = (\bar{t}\,\gamma_\mu\,t)(\bar{t}\,\gamma_\mu\,t)$,		✓
$O^1_{bb} = (\bar{b}\,\gamma_\mu\,b)(\bar{b}\,\gamma_\mu\,b)$,		
$O^1_{Qt} = (\bar{Q}\,\gamma_\mu\,Q)(\bar{t}\,\gamma^\mu\,t)$,	✓	✓
$O^8_{Qt} = (\bar{Q}\,\gamma_\mu\,T^A\,Q)(\bar{t}\,\gamma^\mu\,T^A\,t)$,	✓	✓
$O^1_{Qb} = (\bar{Q}\,\gamma_\mu\,Q)(\bar{b}\,\gamma^\mu\,b)$,	✓	
$O^8_{Qb} = (\bar{Q}\,\gamma_\mu\,T^A\,Q)(\bar{b}\,\gamma^\mu\,T^A\,b)$,	✓	
$O^1_{QtQb} = (\bar{Q}\,t)\,\varepsilon\,(\bar{Q}\,b)$,	✓	
$O^8_{QtQb} = (\bar{Q}\,T^A\,t)\,\varepsilon\,(\bar{Q}\,T^A\,b)$.	✓	

$$C^{(+)}_{QQ} = \frac{1}{2}C^1_{QQ} + \frac{1}{6}C^8_{QQ}$$

Degeneracy in four-top, lifted for $t\bar{t}b\bar{b}$!

Pre-requisite:

$t\bar{t}b\bar{b}$ has a sufficiently large production cross section (~ 3 pb) to exploit differential kinematical information with 300 fb-1 (after Run III)!

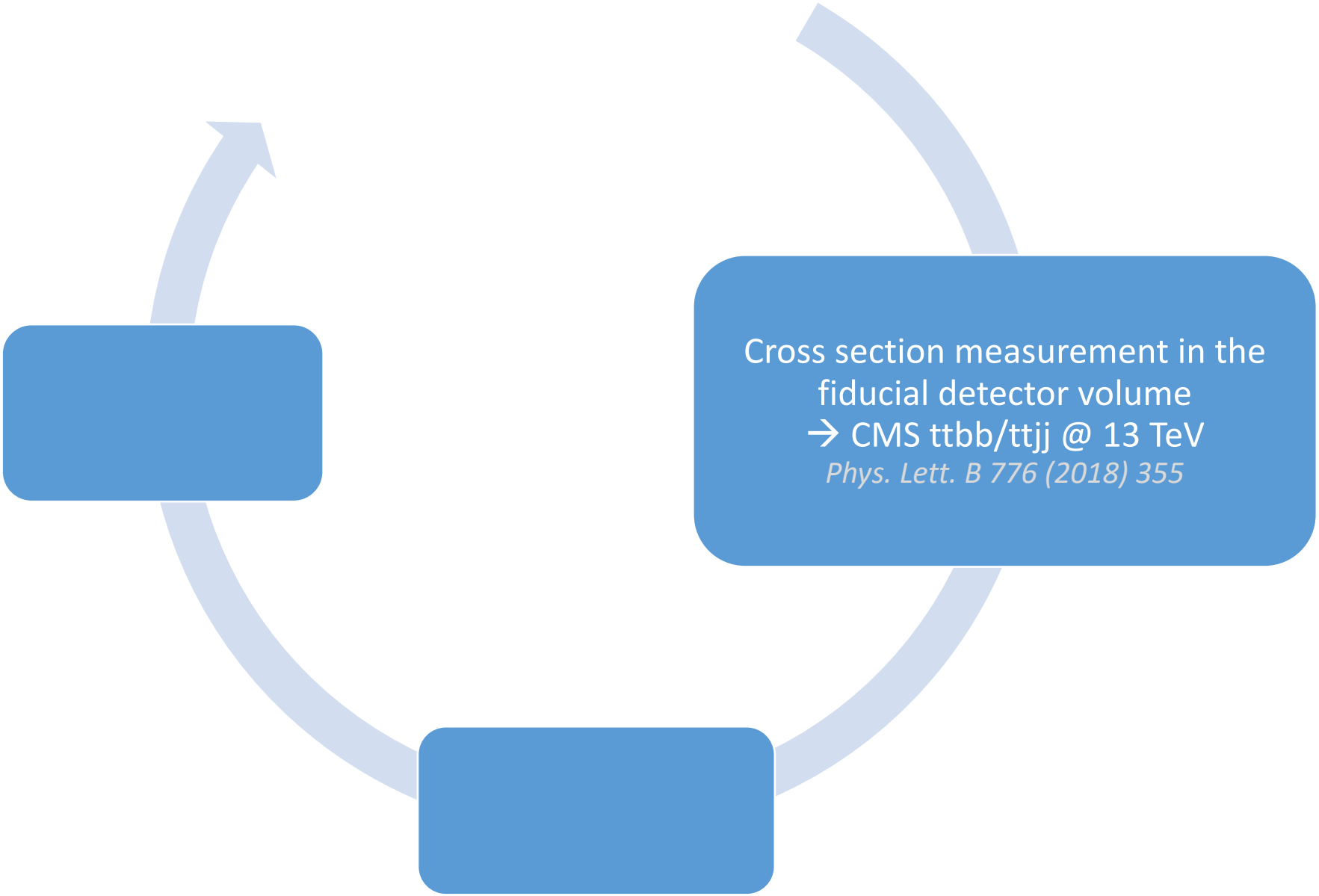
(for comparison: σ_{tttt} ~ 9 fb)

2. $t\bar{t}b\bar{b}$ in SMEFT: comparison to four top

	C. Zhang, Chin. Phys. C42(2018), no. 2 023104	CMS Collaboration CMS-PAS-TOP-17-019	N.P. Hartland et al., arXiv: 1901.05965	J.D'Hondt et al., JHEP 1811 (2018) 131
	4-top (300 fb^{-1}) ($M_{\mathrm{cut}} = 4$ TeV)	4-top (35.8 fb^{-1}) (no M_{cut})	global fit (no M_{cut})	$t\bar{t}b\bar{b}$ (300 fb^{-1}) ($M_{\mathrm{cut}} = 2$ TeV)
C^1_{QQ}	$[-2.8, 2.5]$	$[-2.2, 2.0]$	$[-5.4, 5.2]$	$[-2.1, 2.3]$
C^8_{QQ}	$[-8.4, 7.4]$	n.a.	$[-21, 16]$	$[-4.5, 3.1]$
C^1_{Qt}	$[-2.2, 2.3]$	$[-3.5, 3.5]$	$[-4.9, 4.9]$	$[-2.1, 2.3]$
C^8_{Qt}	$[-5.1, 4.1]$	$[-7.9, 6.6]$	$[-11, 8.7]$	$[-3.9, 3.8]$
	$\mu_{4t} < 1.87$	$\mu_{4t} < 5.22$		

3. Deriving constraints on individual operators: **Sensitivity study**

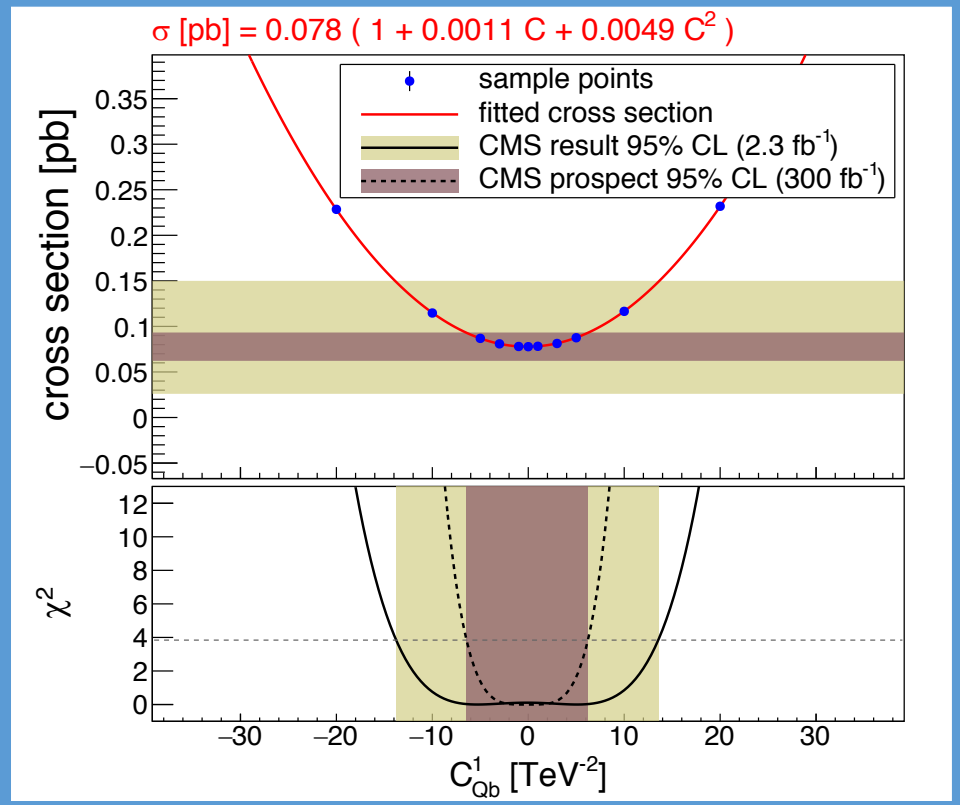
Strategy


Cross section measurement in the fiducial detector volume
→ CMS ttbb/ttjj @ 13 TeV
Phys. Lett. B 776 (2018) 355

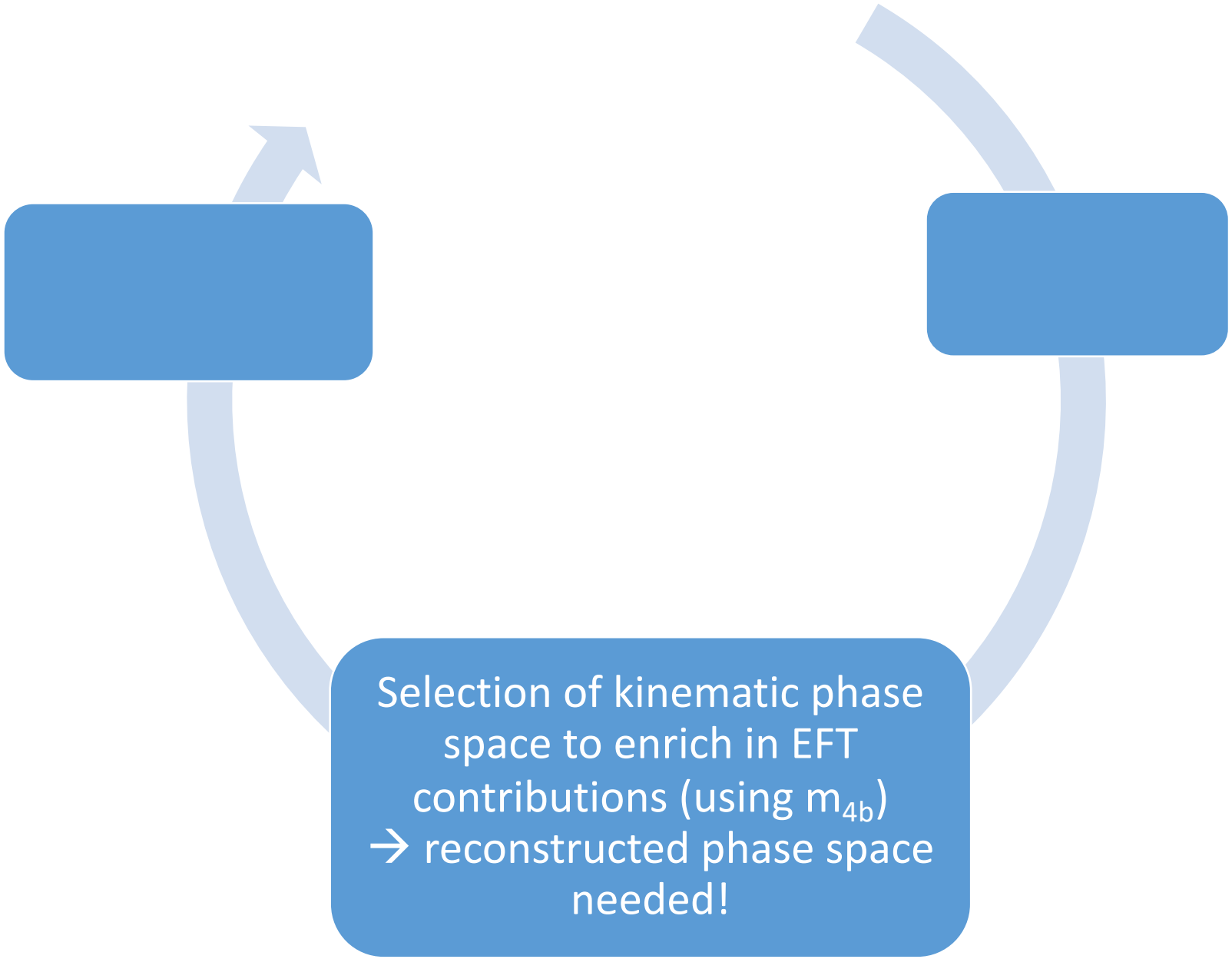
Strategy

Phys. Lett. B 776 (2018) 355

$$\sigma_{t\bar{t}b\bar{b},CMS} = 88 \pm 12(stat.) \pm 29(syst.)\ \mathrm{fb}$$

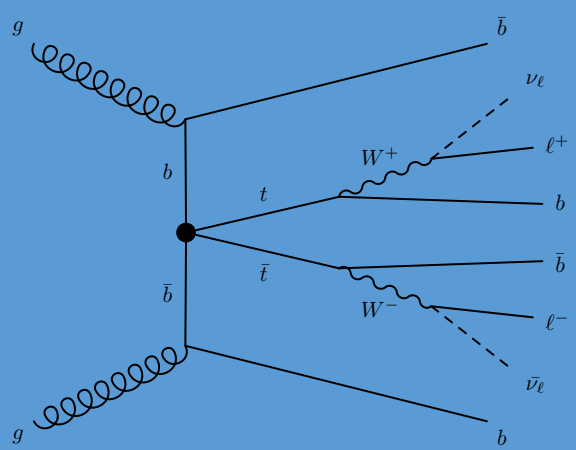


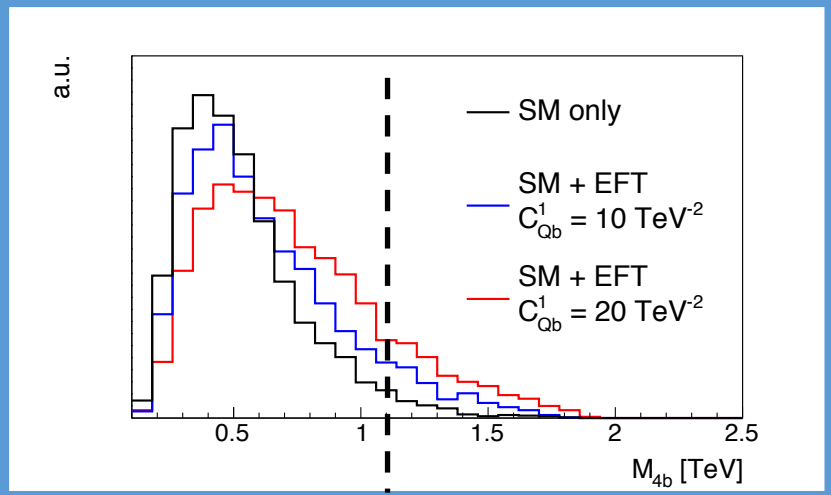
Strategy


Selection of kinematic phase space to enrich in EFT contributions (using m_{4b})
→ reconstructed phase space needed!

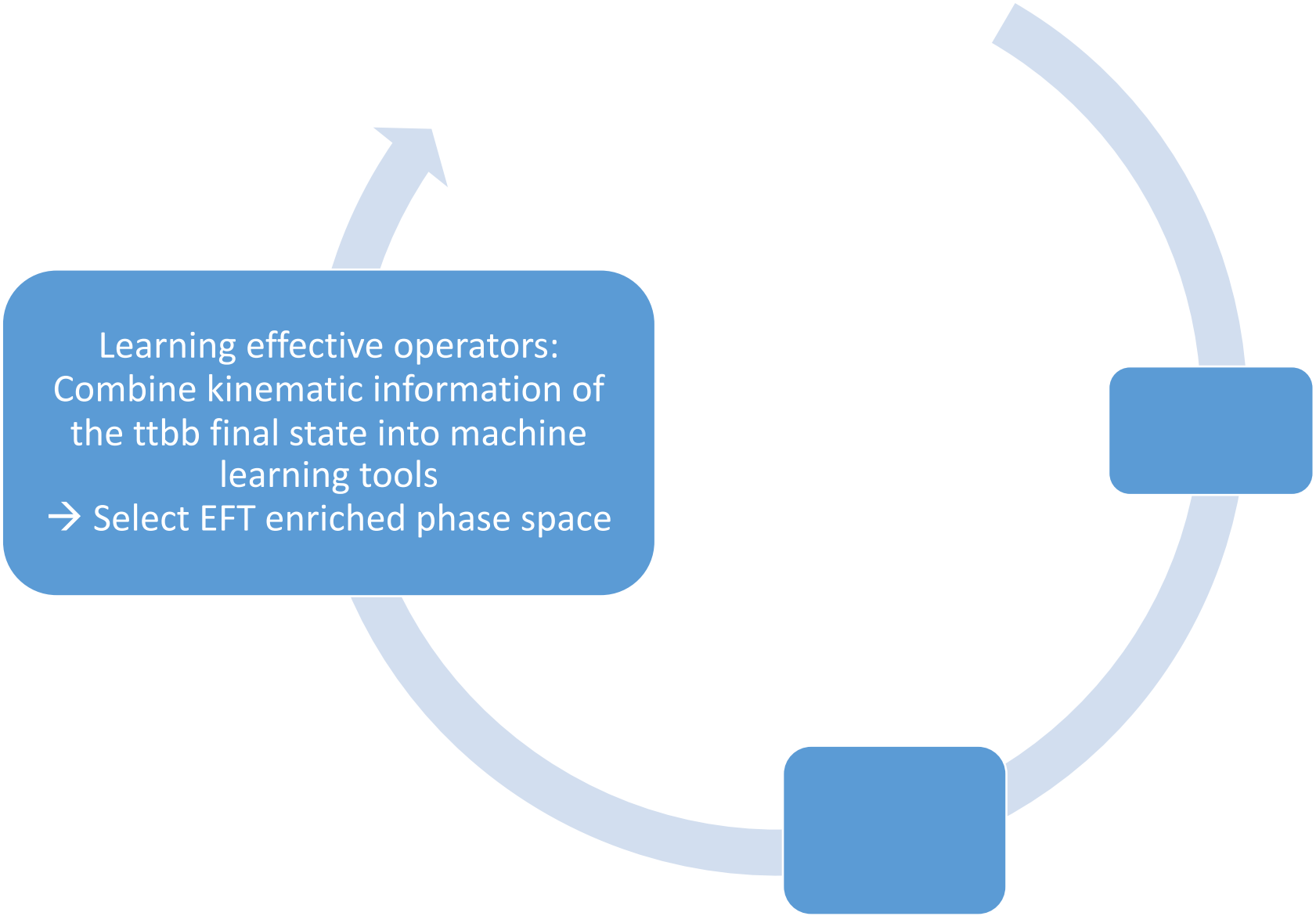
Strategy

- Identify sensitive variable and apply a cut
- Derive cross section dependence on the Wilson coefficients in this EFT-enriched phase space



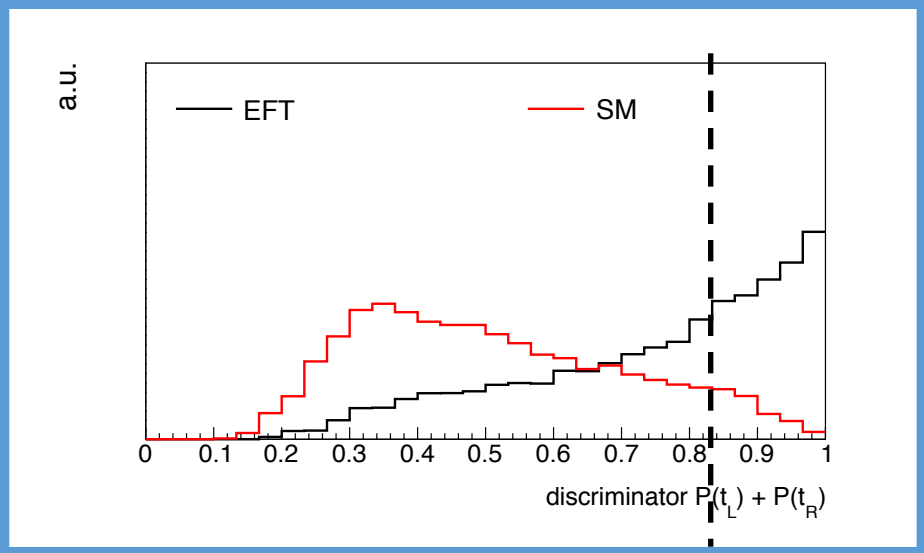


Strategy


Learning effective operators:
Combine kinematic information of the ttbb final state into machine learning tools
→ Select EFT enriched phase space

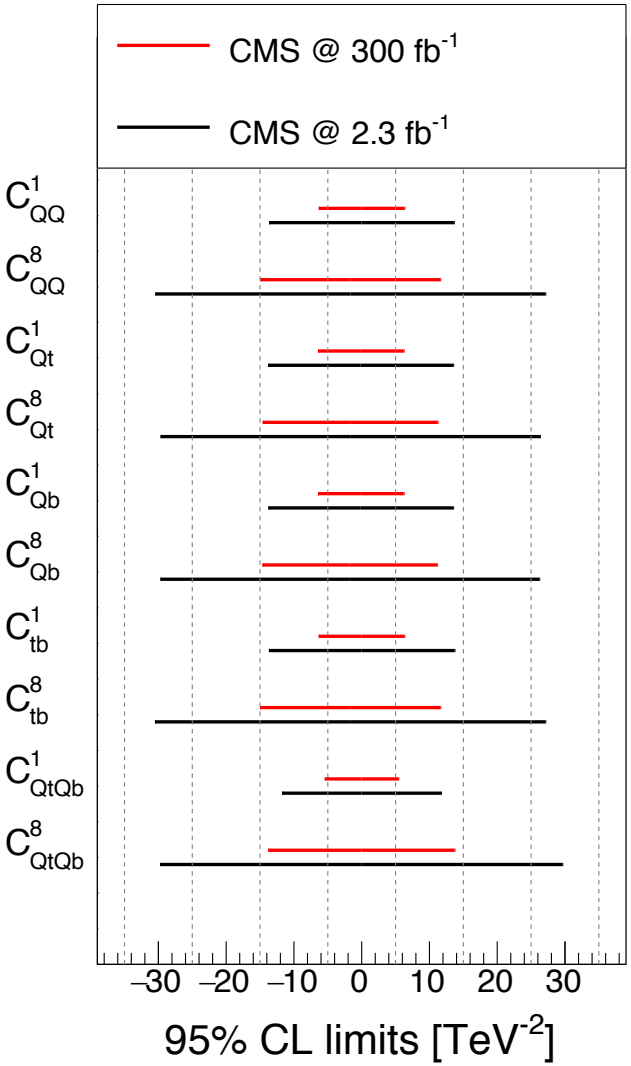
Strategy

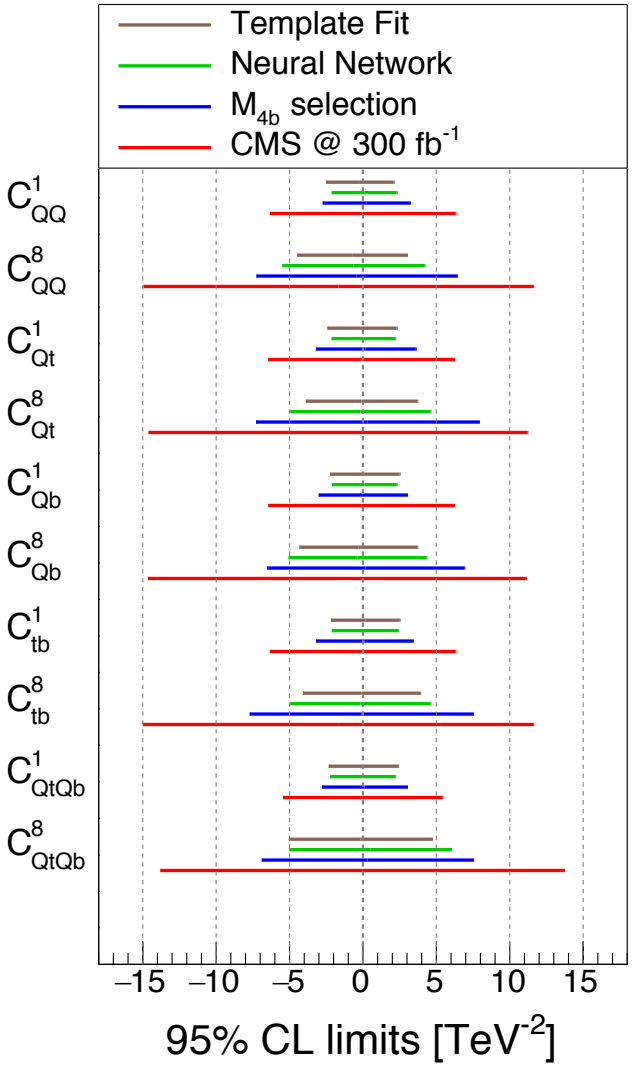
ΔR	m_{inv}	p_T
$\Delta R(\ell_1,\ell_2)$	$m_{inv}(\ell_1,\ell_2)$	$p_T(\ell_1)$
$\Delta R(b_1,b_2)$	$m_{inv}(b_1,b_2)$	$p_T(\ell_2)$
$\Delta R(b_1,\ell_2)$	$m_{inv}(b_1,\ell_2)$	$p_T(b_1)$
$\Delta R(b_2,\ell_1)$	$m_{inv}(b_2,\ell_1)$	$p_T(b_2)$
$\Delta R(add_1,add_2)$	$m_{inv}(add_1,add_2)$	$p_T(add_1)$
	$m_{inv}(b_1,b_2,add_1,add_2)$	$p_T(add_2)$
	$m_{inv}(\ell_1,\ell_2,b_1,b_2,add_1,add_2)$	



Summary of individual limits

Summary of the obtained (projected) 95% CL constraints on all relevant operators (one-by-one).





4. Improving sensitivity with multiple effective operators simultaneously

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

case study: operators with right-handed top currents (t_R) or left-handed top currents (t_L)

Learning the effective operators

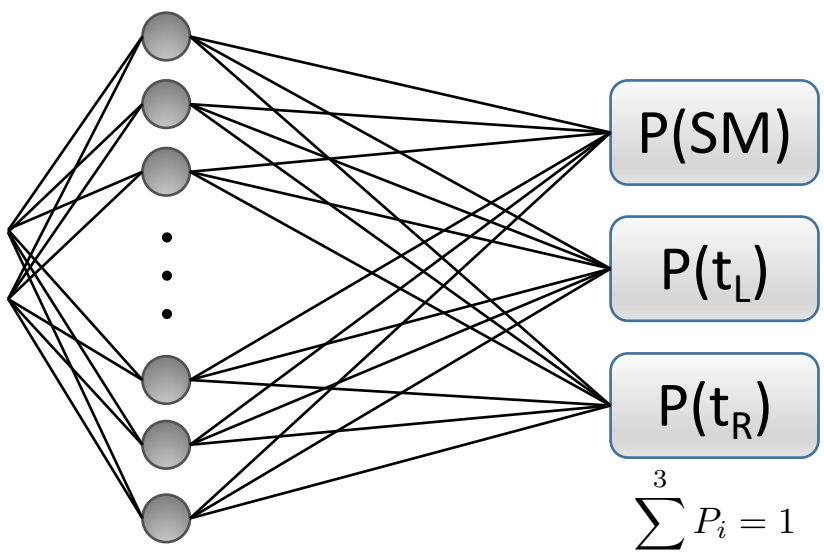
- Combine all available kinematics in a (shallow) neural network (NN) to select EFT enriched phase space.

- Instead of a binary classifier (SM vs EFT), we exploit **multi-class** structure to also **distinguish amongst EFT operators** with left-handed top quark currents (t_L) and with right-handed top quark currents (t_R)!

- **<u>Important note</u>**: training performed on pure SM and pure EFT (only quadratic comtribution, **no interference**!). Including interference in the training is an interesting case-study for the future!

18 kinematic input observables

ΔR	m_{inv}	p_T
$\Delta R(\ell_1,\ell_2)$	$m_{inv}(\ell_1,\ell_2)$	$p_T(\ell_1)$
$\Delta R(b_1,b_2)$	$m_{inv}(b_1,b_2)$	$p_T(\ell_2)$
$\Delta R(b_1,\ell_2)$	$m_{inv}(b_1,\ell_2)$	$p_T(b_1)$
$\Delta R(b_2,\ell_1)$	$m_{inv}(b_2,\ell_1)$	$p_T(b_2)$
$\Delta R(add_1,add_2)$	$m_{inv}(add_1,add_2)$	$p_T(add_1)$
	$m_{inv}(b_1,b_2,add_1,add_2)$	$p_T(add_2)$
	$m_{inv}(\ell_1,\ell_2,b_1,b_2,add_1,add_2)$	



$$\sum_{i=1}^{3} P_i = 1$$

Learning the effective operators

How to combine the network outputs?

	Desired Discrimination	Combined NN Output used for limits
only t_L operator	SM vs t_L	$\frac{P(t_L)}{P(t_L)+P(SM)}$
only t_R operator	SM vs t_R	$\frac{P(t_R)}{P(t_R)+P(SM)}$
including both t_L and t_R operators	EFT vs SM	$P(t_L)+P(t_R)$
	t_L vs t_R	$\frac{P(t_L)}{P(t_L)+P(t_R)}$

One operator at a time: dedicated SM vs t_L/t_R outputs

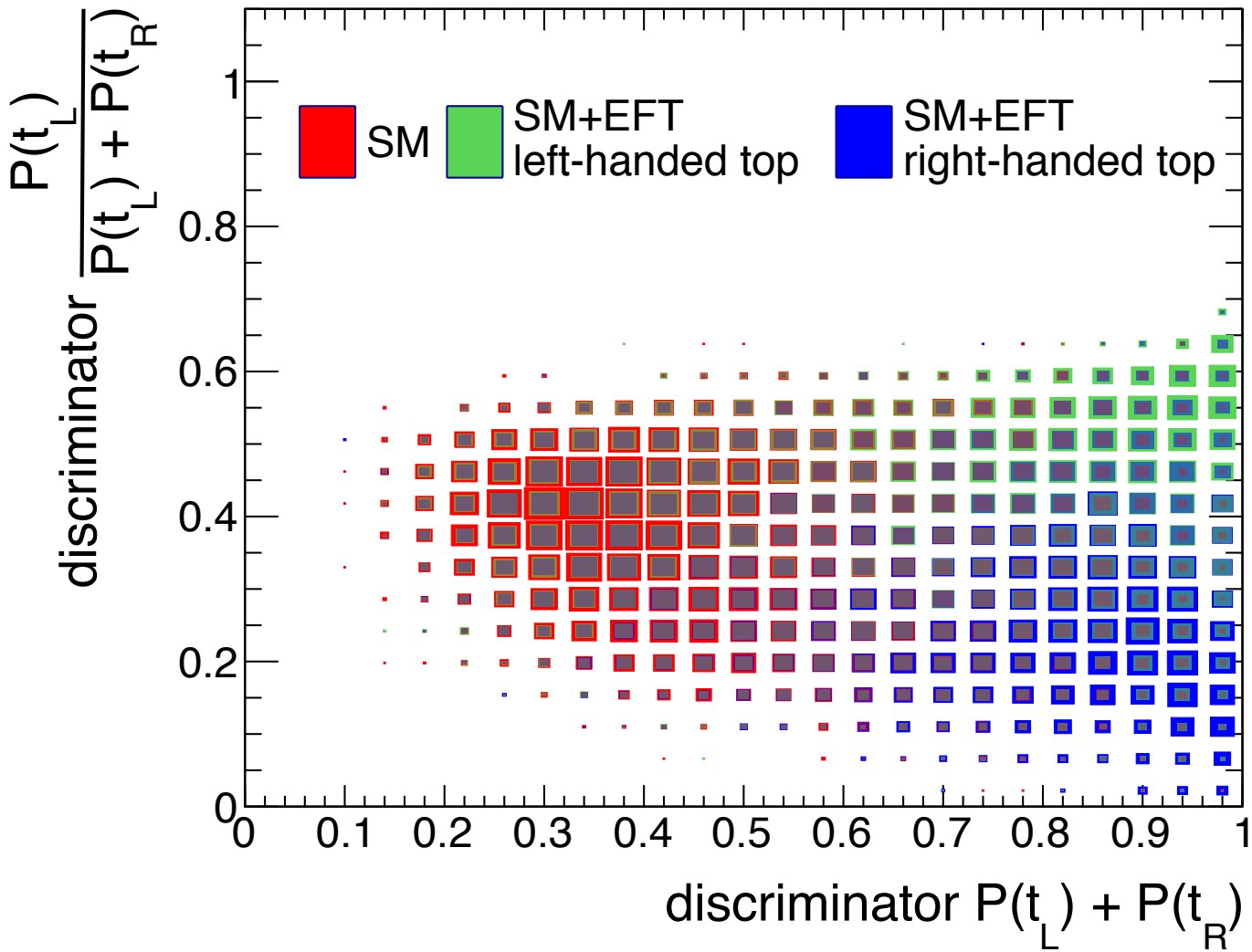
Multiple operators: SM vs EFT and t_L vs t_R outputs

Learning the effective operators

multiple operators

2-dim phase space of NN outputs

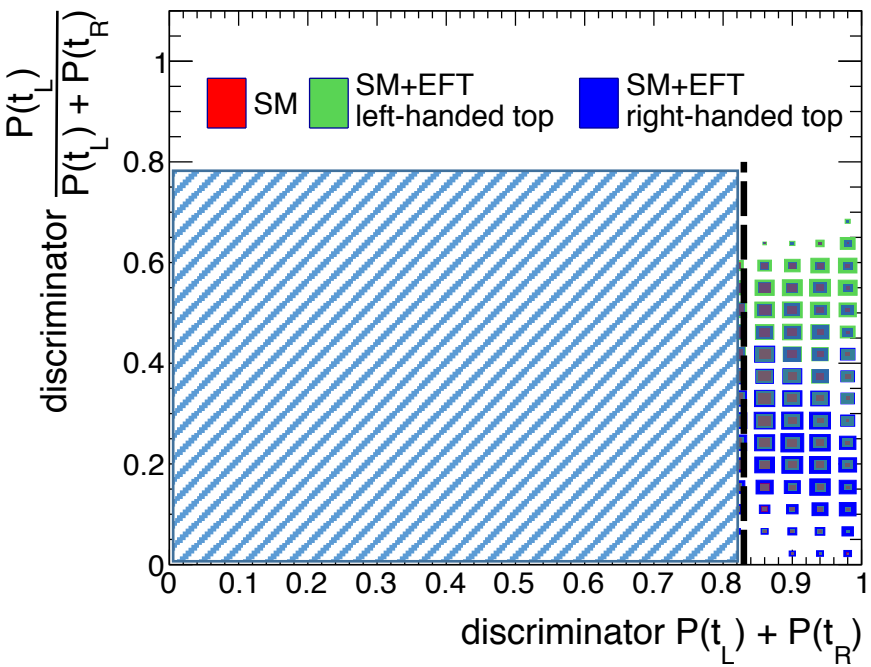
- x-axis: SM vs EFT (t_L and t_R)
- y-axis: t_L vs t_R

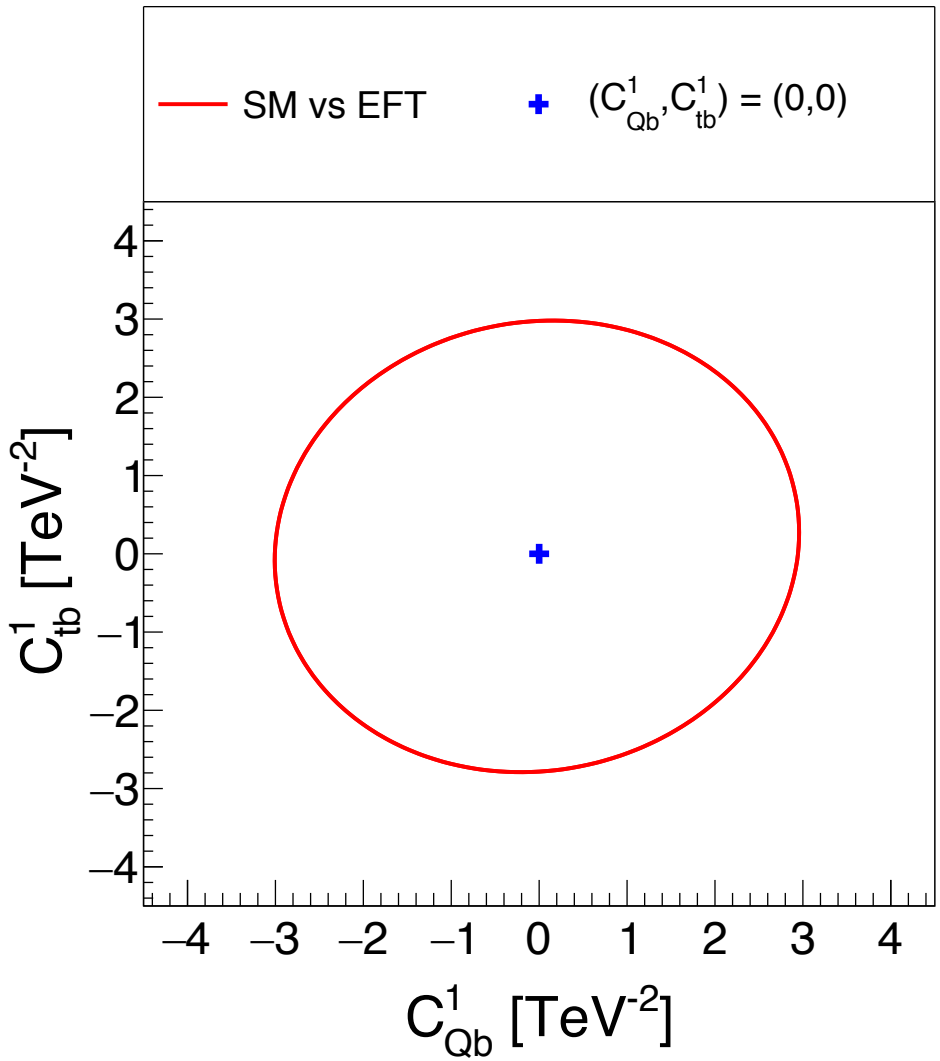


Learning the effective operators
multiple operators

Case-study: Consider two non-zero Wilson coefficients: C^1_{tb} and C^1_{Qb}

→ Assume an observation of the SM: $(C^1_{tb}, C^1_{Qb}) = (0,0)$

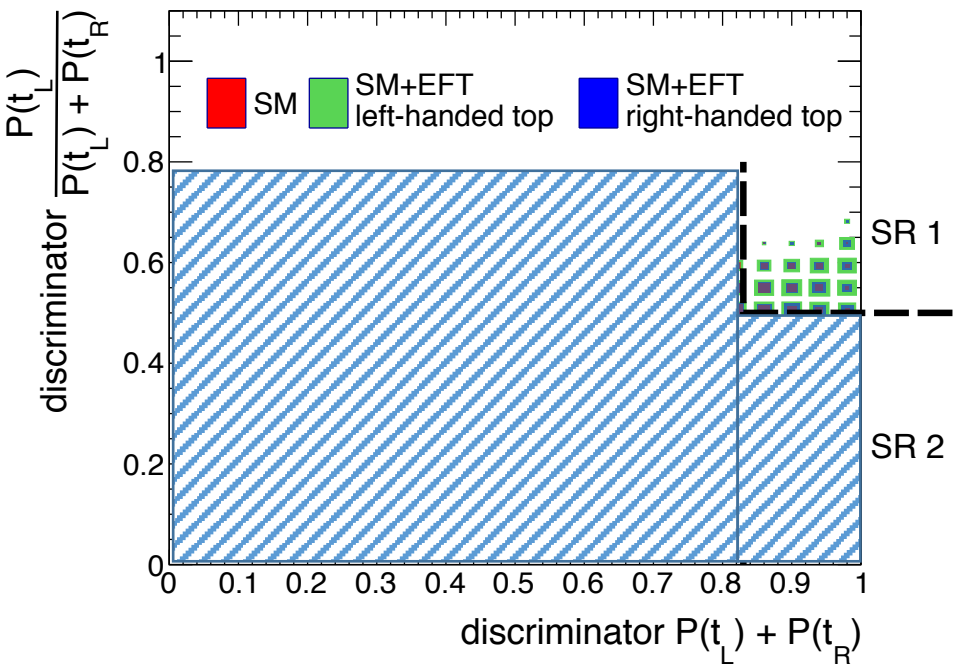


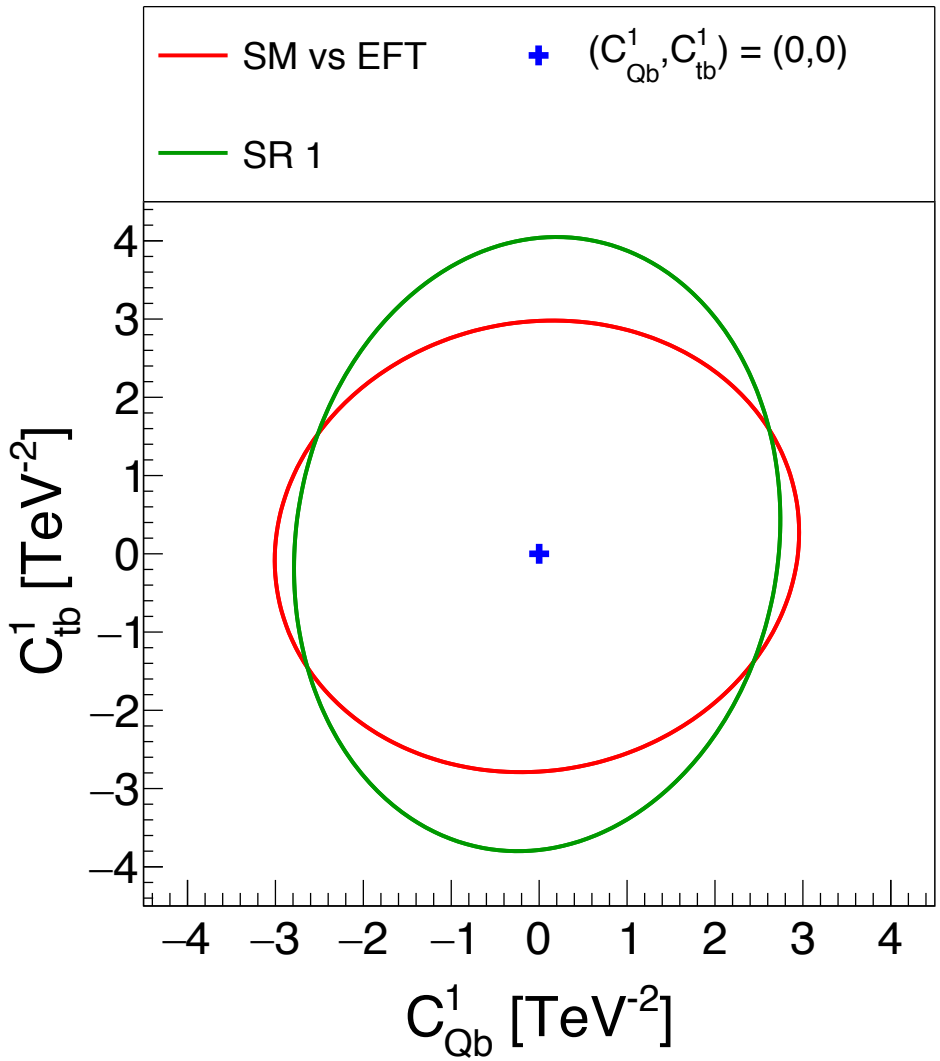


Learning the effective operators
multiple operators

Case-study: Consider two non-zero Wilson coefficients: C^1_{tb} and C^1_{Qb}

→ Assume an observation of the SM: $(C^1_{tb}, C^1_{Qb}) = (0,0)$

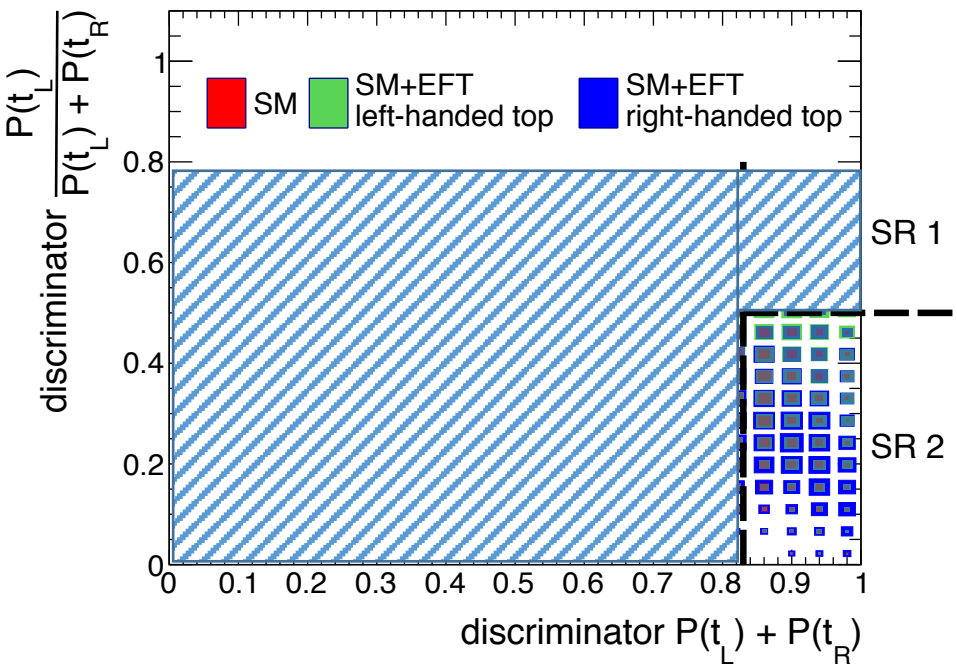


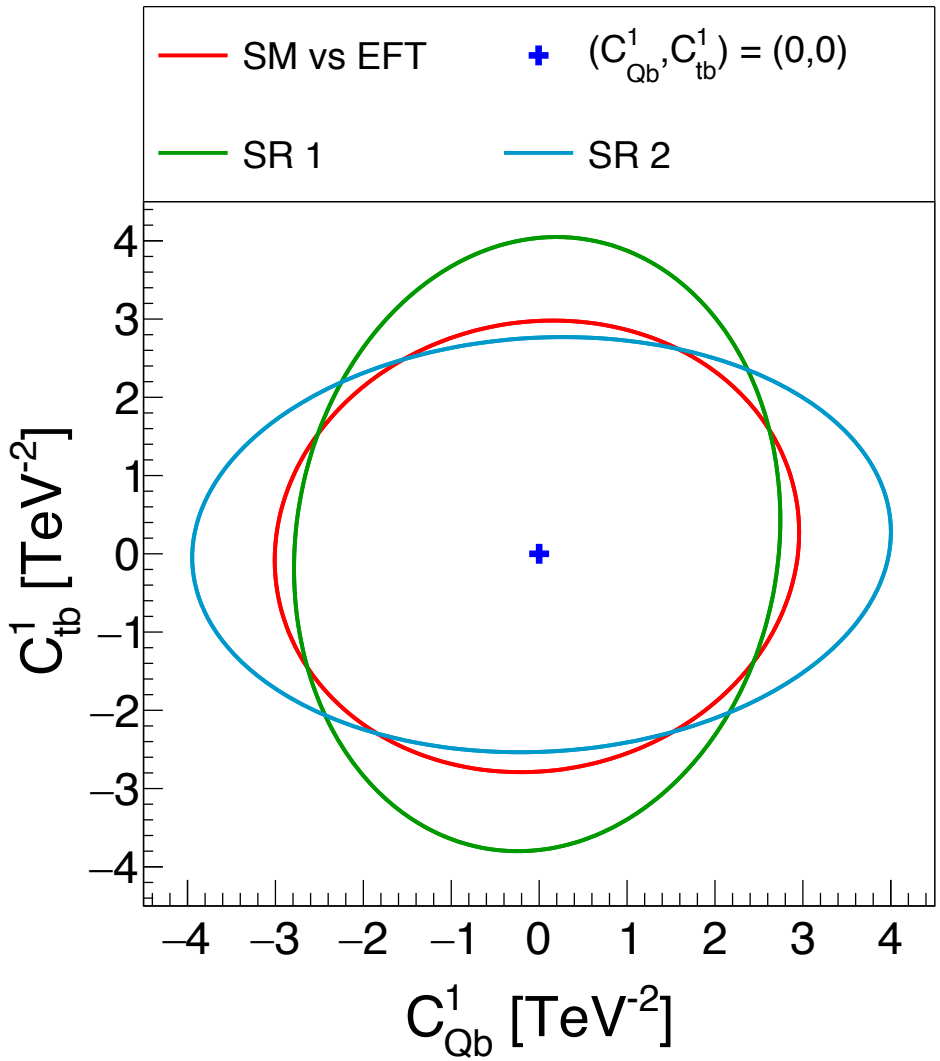


Learning the effective operators
multiple operators

Case-study: Consider two non-zero Wilson coefficients: C^1_{tb} and C^1_{Qb}

→ Assume an observation of the SM: $(C^1_{tb}, C^1_{Qb}) = (0,0)$

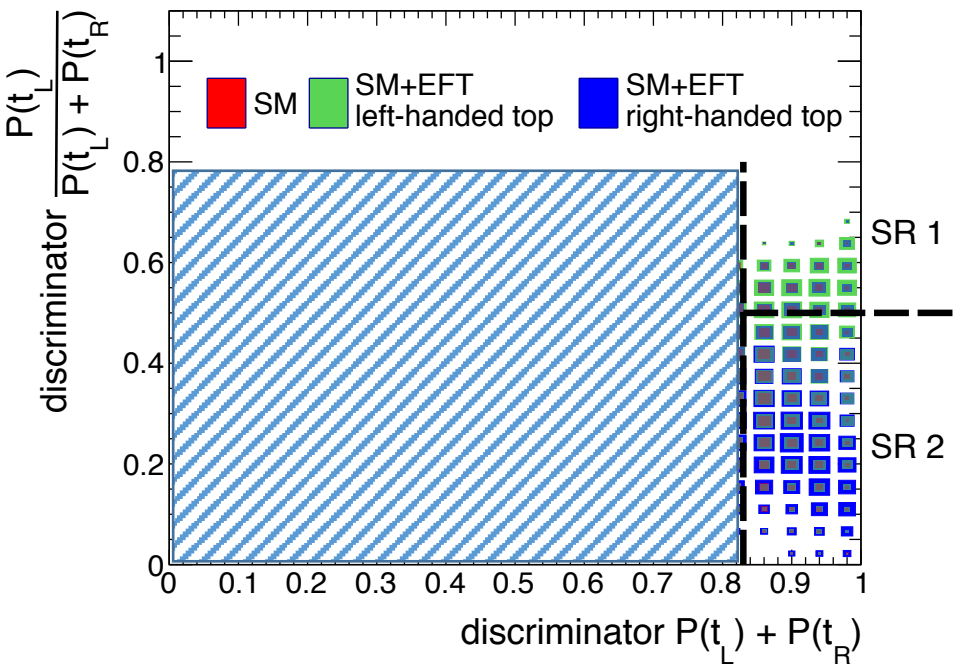


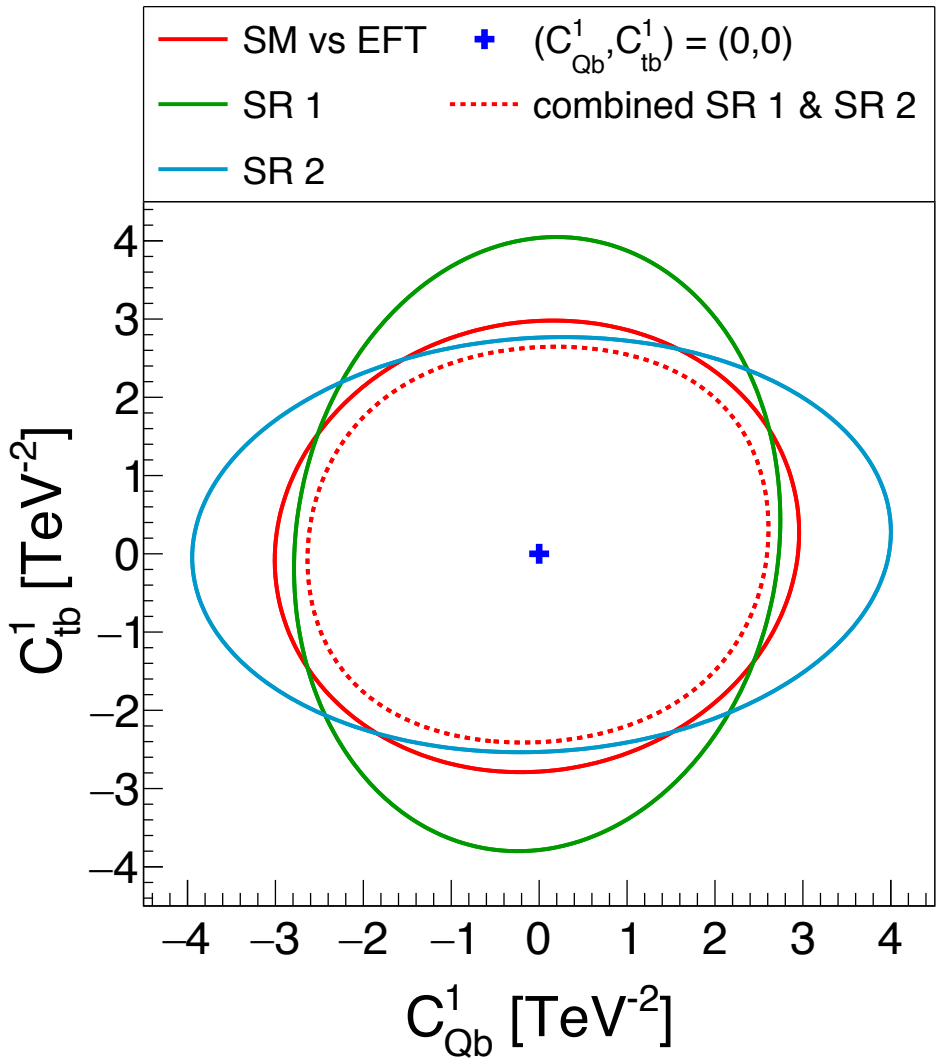


Learning the effective operators
multiple operators

Case-study: Consider two non-zero Wilson coefficients: C^1_{tb} and C^1_{Qb}

→ Assume an observation of the SM: $(C^1_{tb}, C^1_{Qb}) = (0,0)$

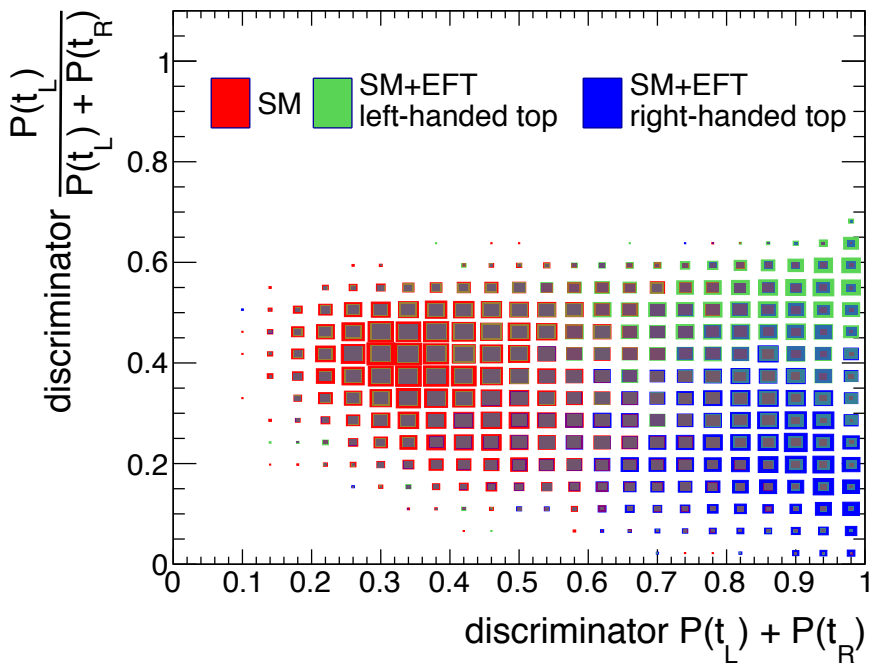


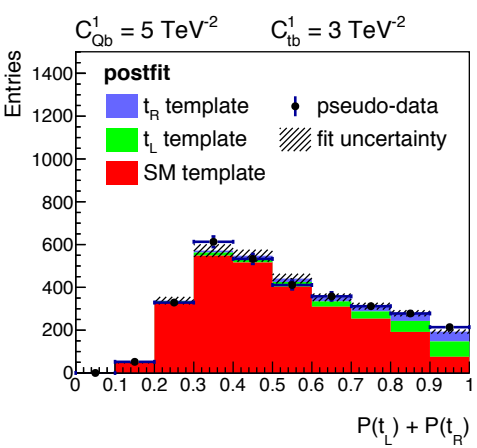


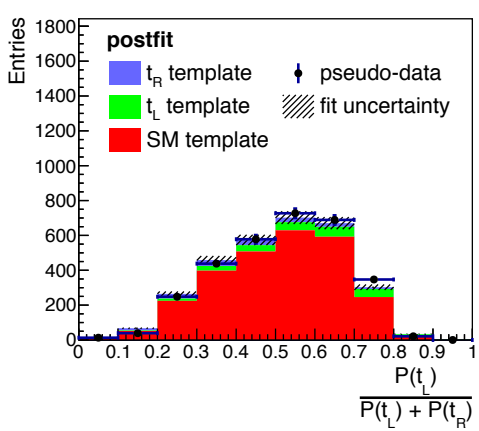
Learning the effective operators
multiple operators

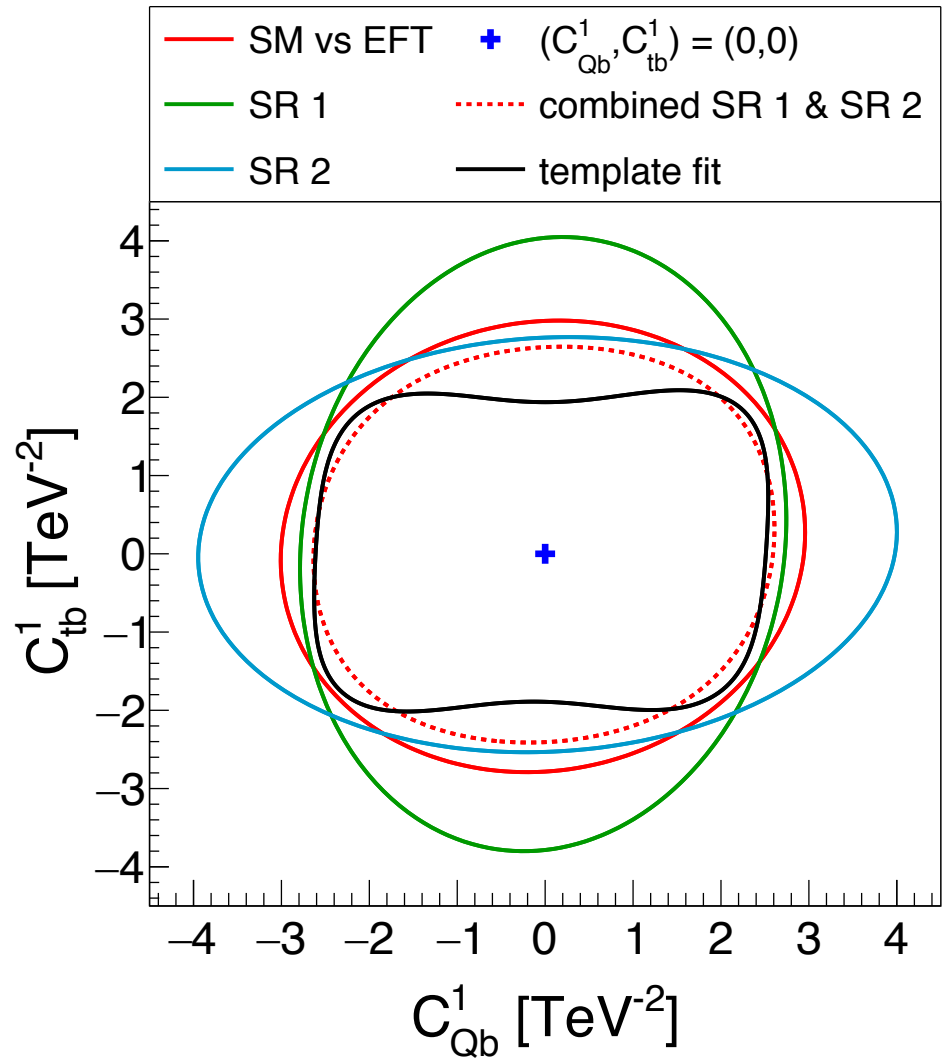
Case-study: Consider two non-zero Wilson coefficients: C_{tb}^1 and C_{Qb}^1

→ Assume an observation of the SM: $(C_{tb}^1, C_{Qb}^1) = (0,0)$





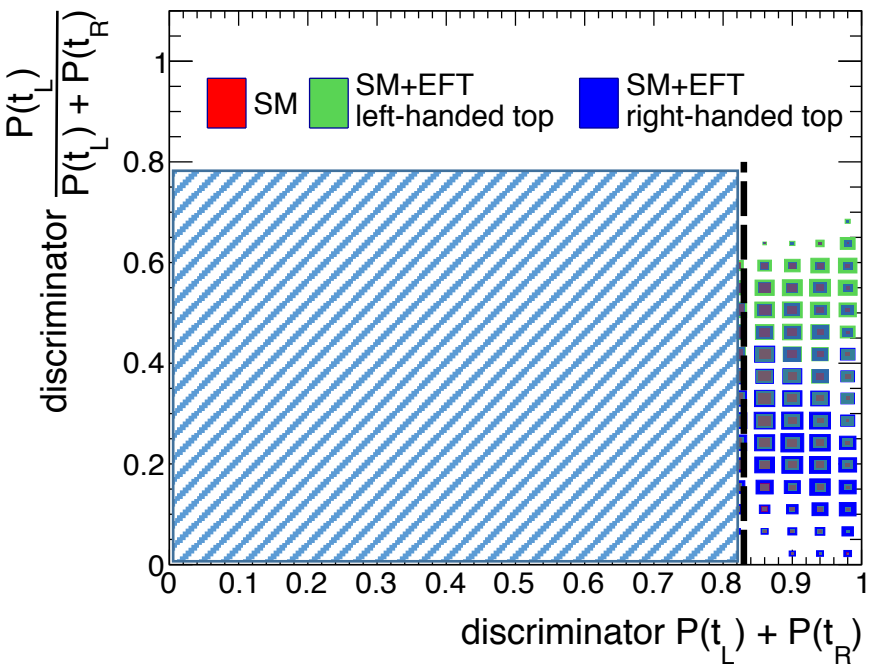


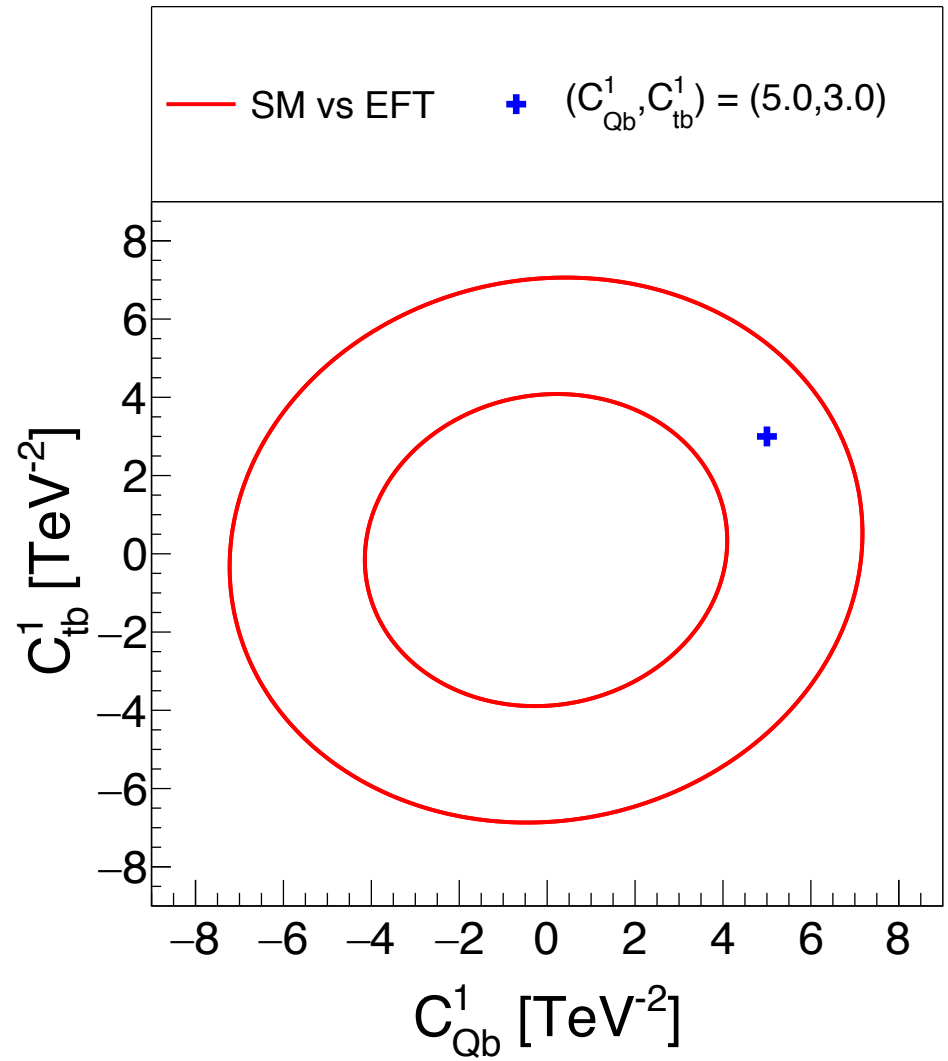


Learning the effective operators
multiple operators

Case-study: Consider two non-zero Wilson coefficients: C^1_{tb} and C^1_{Qb}

→ Assume an observation of EFT signal: $(C^1_{tb}, C^1_{Qb}) = (5,3)$

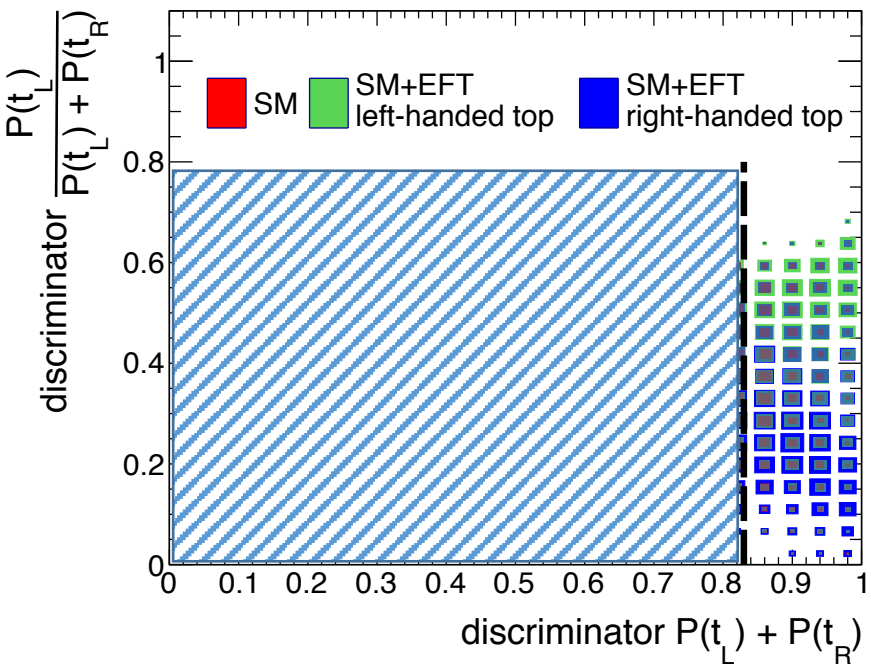


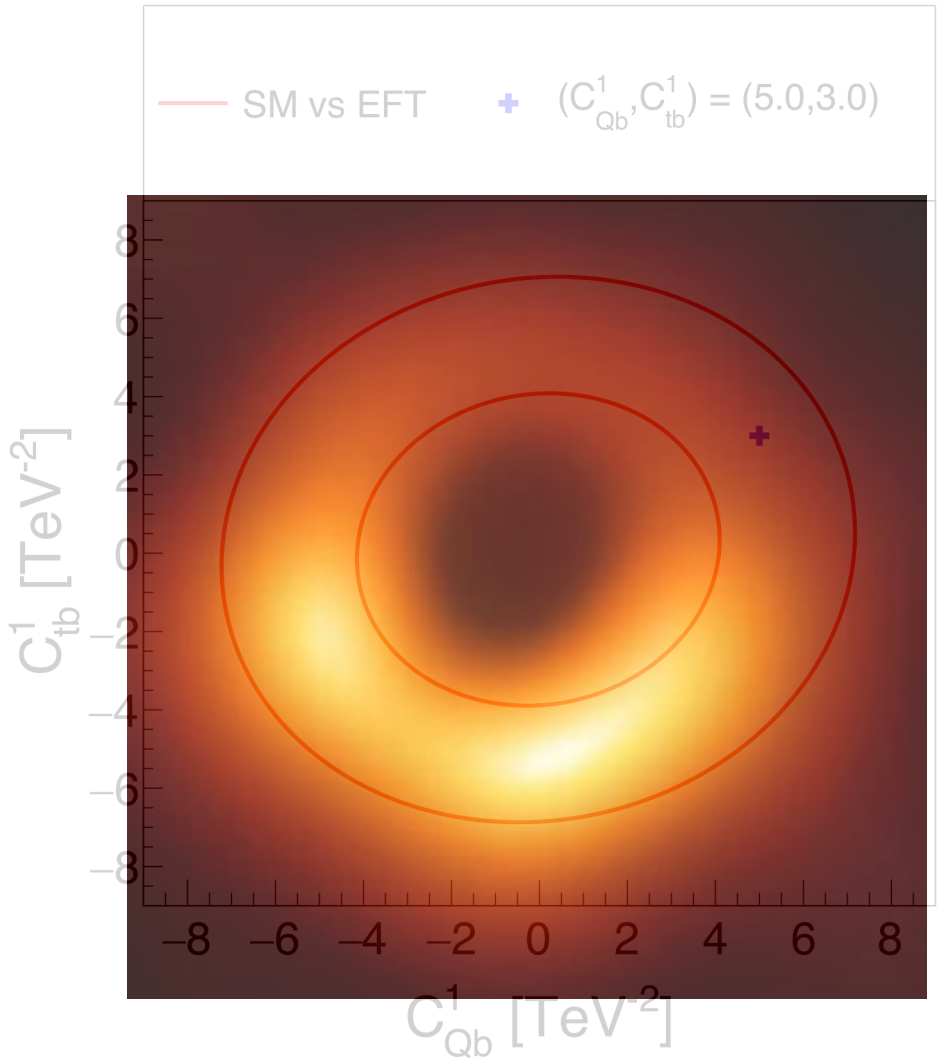


Learning the effective operators
multiple operators

Case-study: Consider two non-zero Wilson coefficients: C^1_{tb} and C^1_{Qb}

→ Assume an observation of EFT signal: $(C^1_{tb}, C^1_{Qb}) = (5,3)$

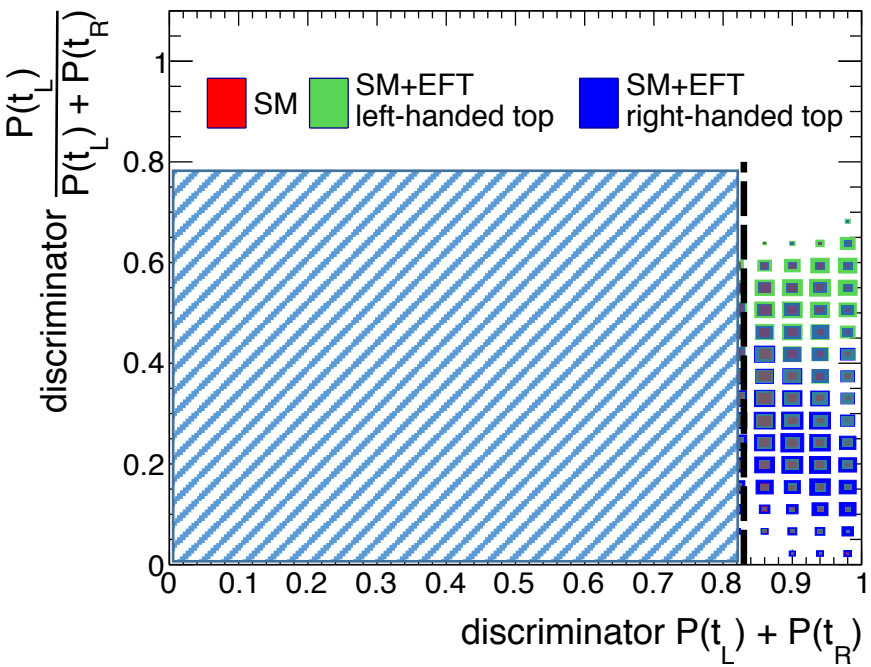


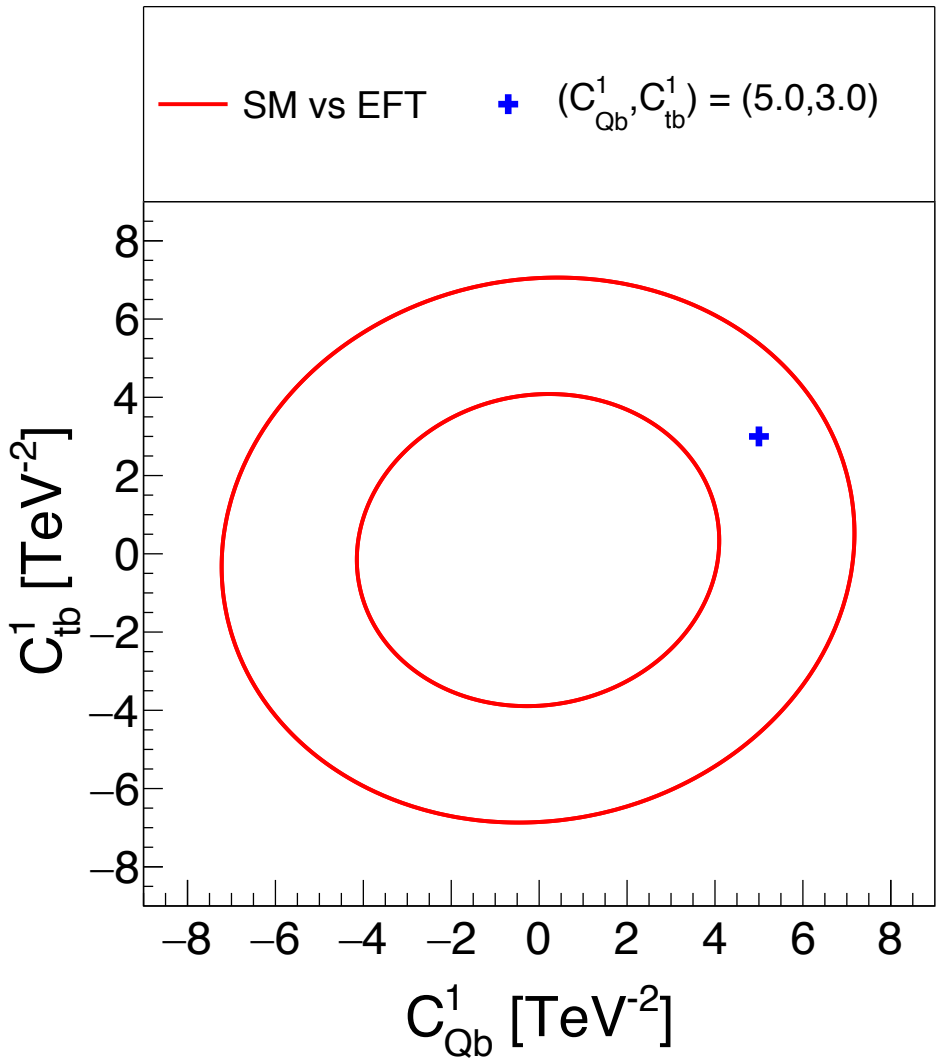


Learning the effective operators
multiple operators

Case-study: Consider two non-zero Wilson coefficients: C^1_{tb} and C^1_{Qb}

→ Assume an observation of EFT signal: $(C^1_{tb}, C^1_{Qb}) = (5,3)$

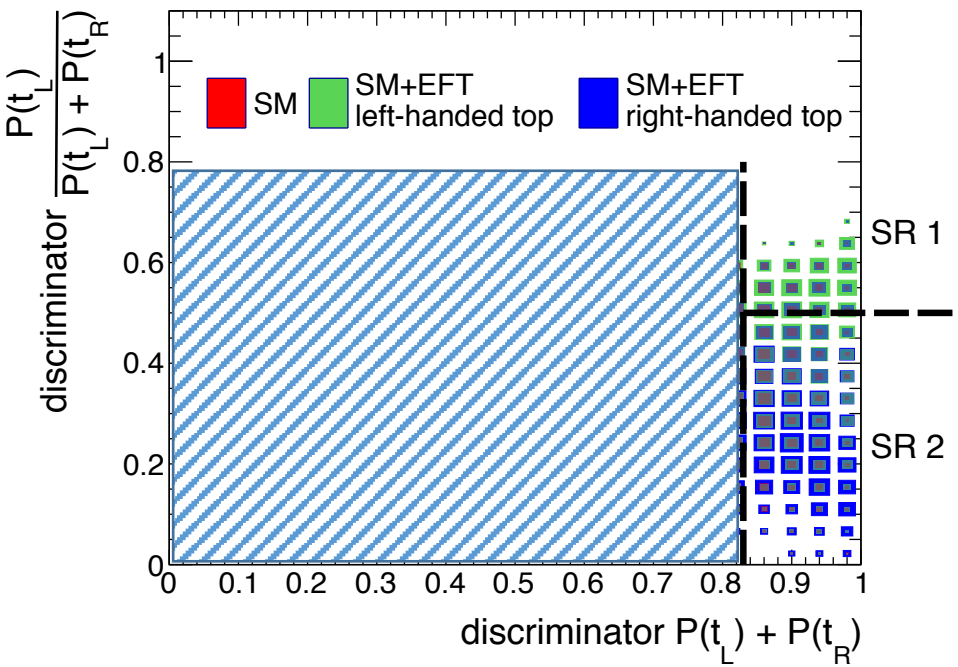


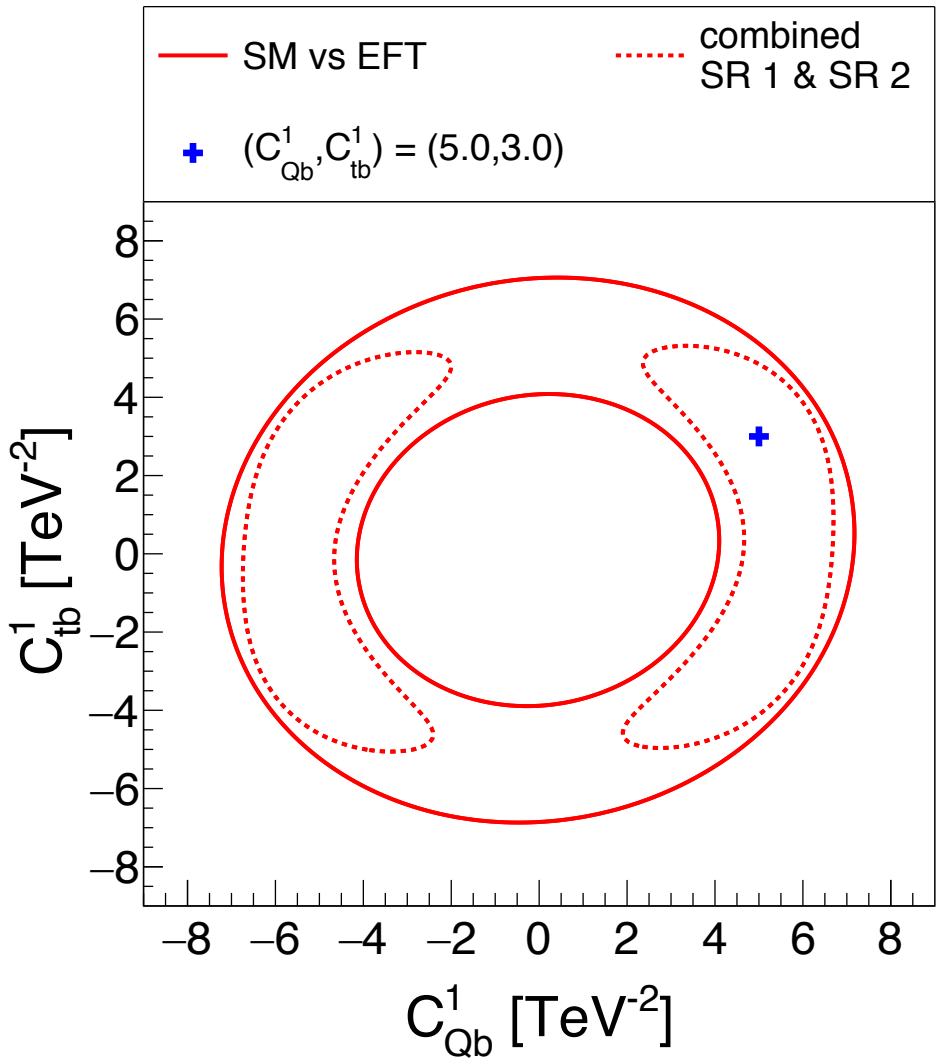


Learning the effective operators
multiple operators

Case-study: Consider two non-zero Wilson coefficients: C_{tb}^{1} and C_{Qb}^{1}

→ Assume an observation of EFT signal: $(C_{tb}^{1}, C_{Qb}^{1}) = (5,3)$

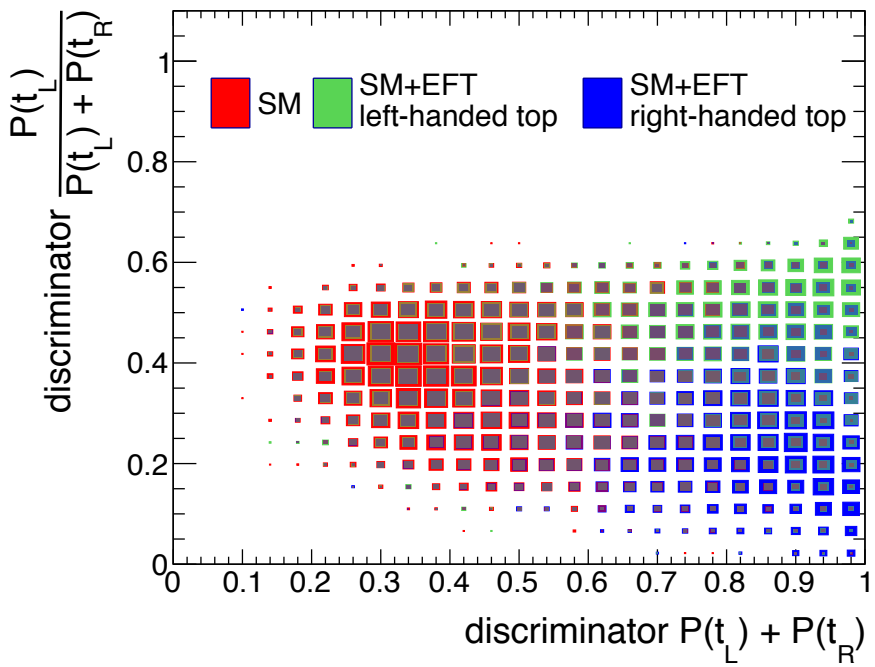


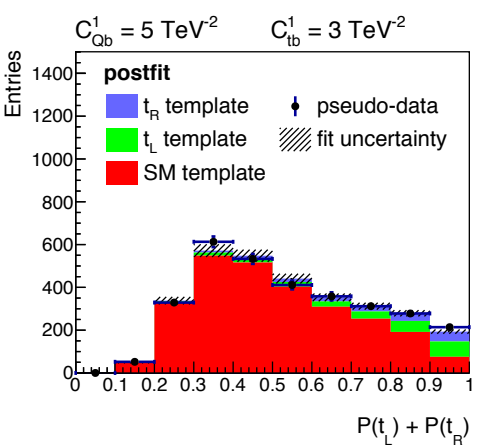


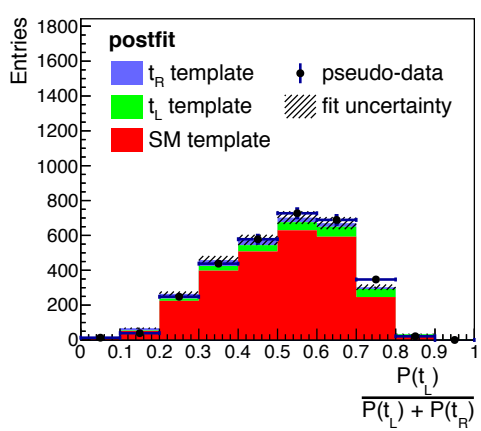
Learning the effective operators
multiple operators

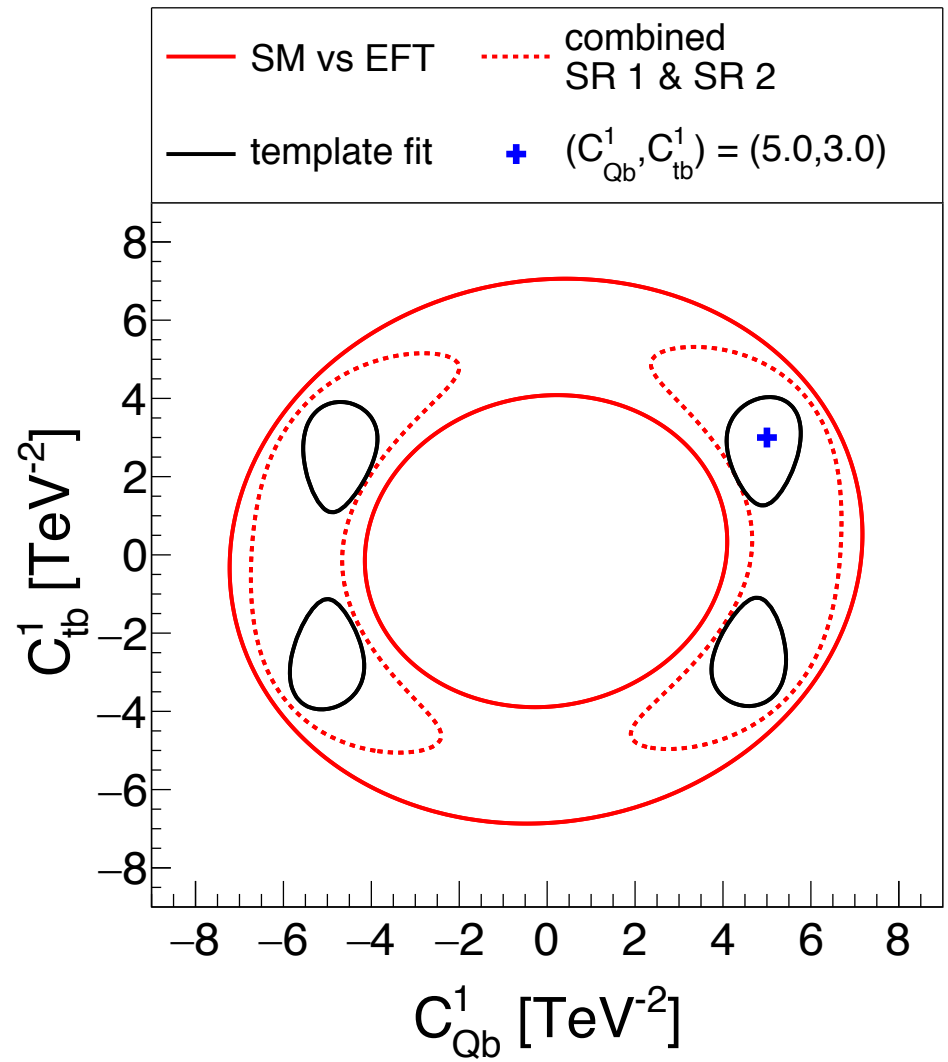
Case-study: Consider two non-zero Wilson coefficients: C_{tb}^1 and C_{Qb}^1

→ Assume an observation of EFT signal: $(C_{tb}^1, C_{Qb}^1) = (5,3)$







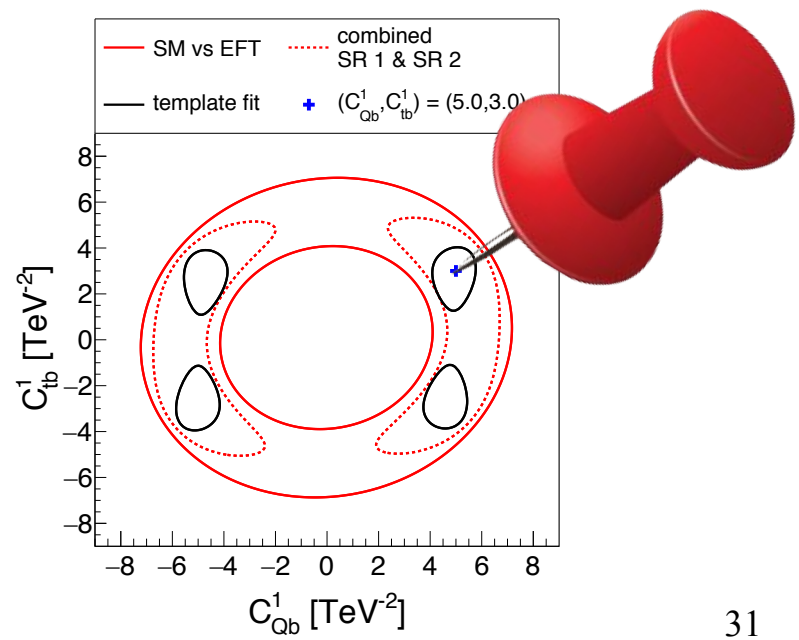


Summary

- $t\bar{t}b\bar{b}$ is an indispensable component in a global fit of the top-quark interactions in the SMEFT at the LHC!
  - Large enough cross section to exploit differential information
  - First direct constraints on a specific set of operators

- Multi-class machine learning algorithms are a suitable tool for interpreting LHC data in this framework!
  - Intrinsically large SMEFT parameter space
  - High-multiplicity final states with inter-correlated information

- Probing multiple SMEFT couplings simultaneously allow to pinpoint (or constrain) more efficiently the origin (absence) of a possible excess!



Backup

Introduction: $t\bar{t}b\bar{b}$ production

I associate ttbb to:

A Higgs boson measurements

B SM measurements

C Theory calculations (simulations)

D BSM searches

Vote Results

Introduction: $t\bar{t}b\bar{b}$ production

I associate ttbb to:

- (A) Higgs boson measurements
- (B) SM measurements
- (C) Theory calculations (simulations)
- (D) BSM searches

Vote Results

A. $t\bar{t}b\bar{b}$ is important background for $t\bar{t}H$ ($H \to b\bar{b}$). Recent discovery of this Higgs production mode
CMS: Phys. Rev. Lett. 120 (2018), ATLAS: ArXiv:1411.5621

B. $t\bar{t}b\bar{b}$ ($t\bar{t}b\bar{b}$/ttjj) has therefore been measured by CMS and ATLAS (7, 8 & 13 TeV)
CMS: Phys. Lett. B 746 (2015) 132, Phys. Lett. B 776 (2018) 355, ATLAS: Phys. Rev. D 89, 072012 (2014), Eur.Phys.J. C76 (2016), no.1, 11

C. Difficult modeling (different mass scales, collinear splitting,...) → large effort from theory community
example: T. Jezo et al. Eur.Phys.J. C78 (2018), no.6, 502

D. ??? → Indispensable component in global fit of top-quark interactions!

$t\bar{t}b\bar{b}$ in SMEFT: comparison to four top

- Some operators can be constrained by four top as well

  ex: C. Zhang Chin. Phys.C42(2018), no. 2 023104

Operator	$t\bar{t}b\bar{b}$	$t\bar{t}t\bar{t}$
$O^1_{QQ} = \frac{1}{2}(\bar{Q}\,\gamma_\mu\,Q)\,(\bar{Q}\,\gamma^\mu\,Q)\,,$	✓	✓
$O^8_{QQ} = \frac{1}{2}(\bar{Q}\,\gamma_\mu\,T^A\,Q)\,(\bar{Q}\,\gamma^\mu\,T^A\,Q)\,,$	✓	✓
$O^1_{tb} = (\bar{t}\,\gamma_\mu\,t)\,(\bar{b}\,\gamma_\mu\,b)\,,$	✓	
$O^8_{tb} = (\bar{t}\,\gamma_\mu T^A\,t)\,(\bar{b}\,\gamma_\mu\,T^A\,b)\,,$	✓	
$O^1_{tt} = (\bar{t}\,\gamma_\mu\,t)\,(\bar{t}\,\gamma_\mu\,t)\,,$		✓
$O^1_{bb} = (\bar{b}\,\gamma_\mu\,b)\,(\bar{b}\,\gamma_\mu\,b)\,,$		
$O^1_{Qt} = (\bar{Q}\,\gamma_\mu\,Q)\,(\bar{t}\,\gamma^\mu\,t)\,,$	✓	✓
$O^8_{Qt} = (\bar{Q}\,\gamma_\mu\,T^A\,Q)\,(\bar{t}\,\gamma^\mu\,T^A\,t)\,,$	✓	✓
$O^1_{Qb} = (\bar{Q}\,\gamma_\mu\,Q)\,(\bar{b}\,\gamma^\mu\,b)\,,$	✓	
$O^8_{Qb} = (\bar{Q}\,\gamma_\mu\,T^A\,Q)\,(\bar{b}\,\gamma^\mu\,T^A\,b)\,,$	✓	
$O^1_{QtQb} = (\bar{Q}\,t)\,\varepsilon\,(\bar{Q}\,b)\,,$	✓	
$O^8_{QtQb} = (\bar{Q}\,T^A\,t)\,\varepsilon\,(\bar{Q}\,T^A\,b)\,.$	✓	

$$C^{(+)}_{QQ} = \frac{1}{2}C^1_{QQ} + \frac{1}{6}C^8_{QQ}$$

Degeneracy in four-top, lifted for $t\bar{t}b\bar{b}$!

Operator	4-top ($M_{cut} = 2$ TeV)	4-top ($M_{cut} = 3$ TeV)	4-top ($M_{cut} = 4$ TeV)	this work ($M_{cut} = 2$ TeV)
C^1_{QQ}	$[-3.9, 3.5]$	$[-2.9, 2.6]$	$[-2.8, 2.5]$	$[-2.1, 2.3]$
C^8_{QQ}	$[-11.8, 10.5]$	$[-8.8, 7.8]$	$[-8.4, 7.4]$	$[-4.5, 3.1]$
C^1_{Qt}	$[-3.2, 3.3]$	$[-2.4, 2.4]$	$[-2.2, 2.3]$	$[-2.1, 2.3]$
C^8_{Qt}	$[-7.4, 5.8]$	$[-5.4, 4.3]$	$[-5.1, 4.1]$	$[-3.9, 3.8]$

→ @ 300 fb^{-1}

Model building and generator software details

Dimension-6 four-fermion EFT operators
Feynrules model provided by LHC TOP WG

UFO output: "Dim6Top"

LO matrix element calculation
MadGraph

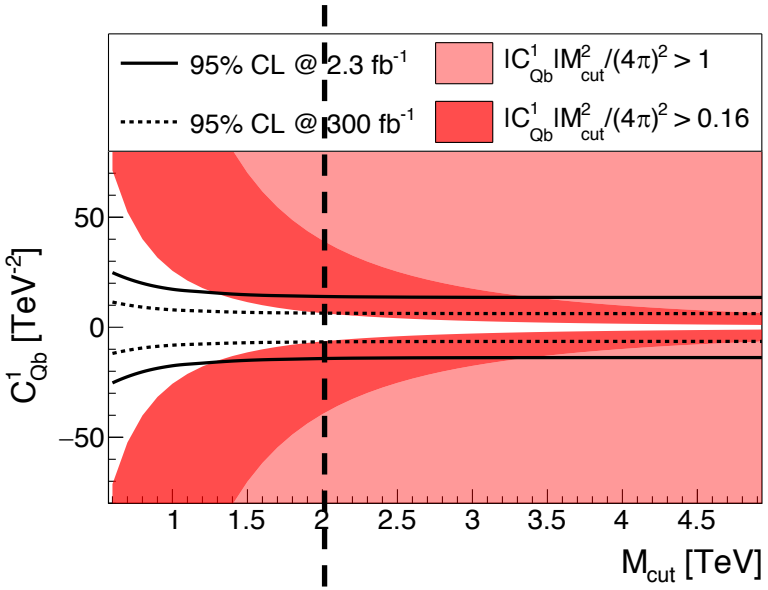
Visible phase space at particle level

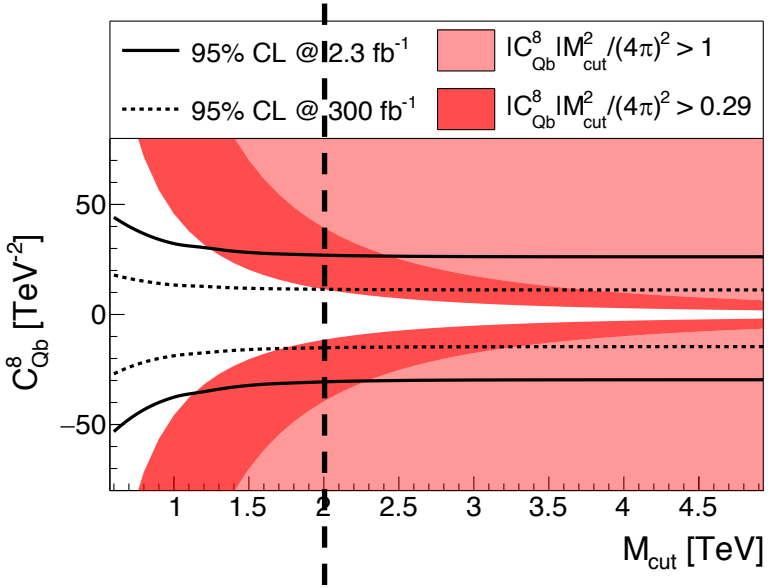
Parton showering
Pythia 8

Detector simulation and event reconstruction
Delphes

Phase space after event reconstruction and selection

EFT validity



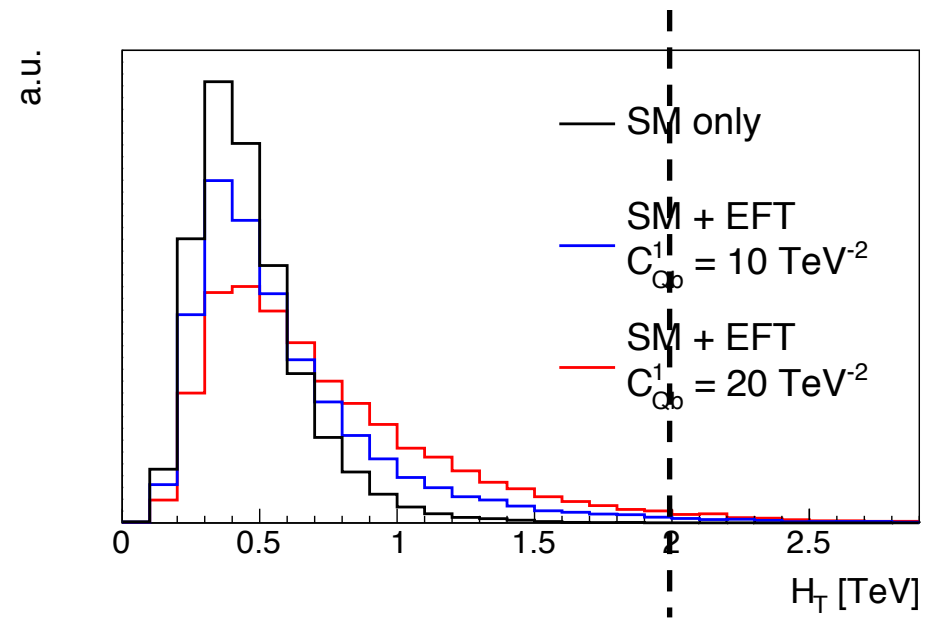


M_{cut} = 2 TeV

$$\frac{c_i}{\Lambda^2}E^2 \equiv C_i E^2 < C_i M_{cut}^2 \lesssim (4\pi)^2$$

Fix Λ = 1 TeV and express limits in [TeV^{-2}]

All energy scales associated to the final state are imposed to be below M_{cut}.
→ H_T (scalar sum of all visible final state objects) is a good example.



Strategy

Learning effective operators: Combine kinematic information of the ttbb final state into machine learning tools
→ Select EFT enriched phase space
→ Distinguish amongst EFT operators!

Cross section measurement in the fiducial detector volume
→ CMS ttbb/ttjj @ 13 TeV
Phys. Lett. B 776 (2018) 355

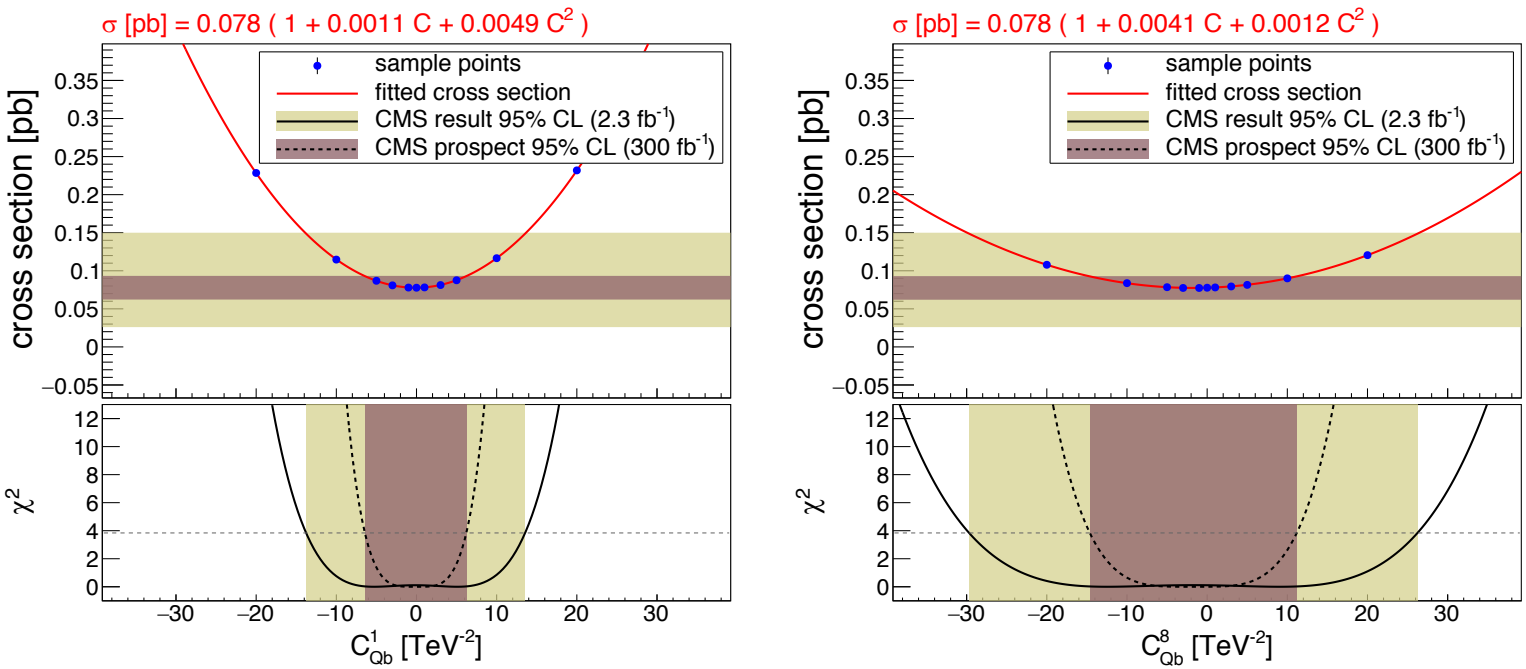
Selection of kinematic phase space to enrich in EFT contributions (using m_{4b})
→ reconstructed phase space needed!

Cross section in the fiducial detector volume

CSM Collaboration, Measurements of $t\bar{t}$ cross sections in association with b jets and inclusive jets and their ratio using dilepton final states in pp collisions at $\sqrt{s}$ = 13 TeV, *Phys. Lett. B 776 (2018) 355*

Integrated luminosity = 2.3 fb^{-1}
Visible phase space definition:
$\sigma_{t\bar{t}b\bar{b},CMS} = 88 \pm 12(stat.) \pm 29(syst.)$ fb

Projections for 300 fb-1: scaled stat. unc. and fixed syst. unc. of 10%
measured xsec = prediction of MadGraph



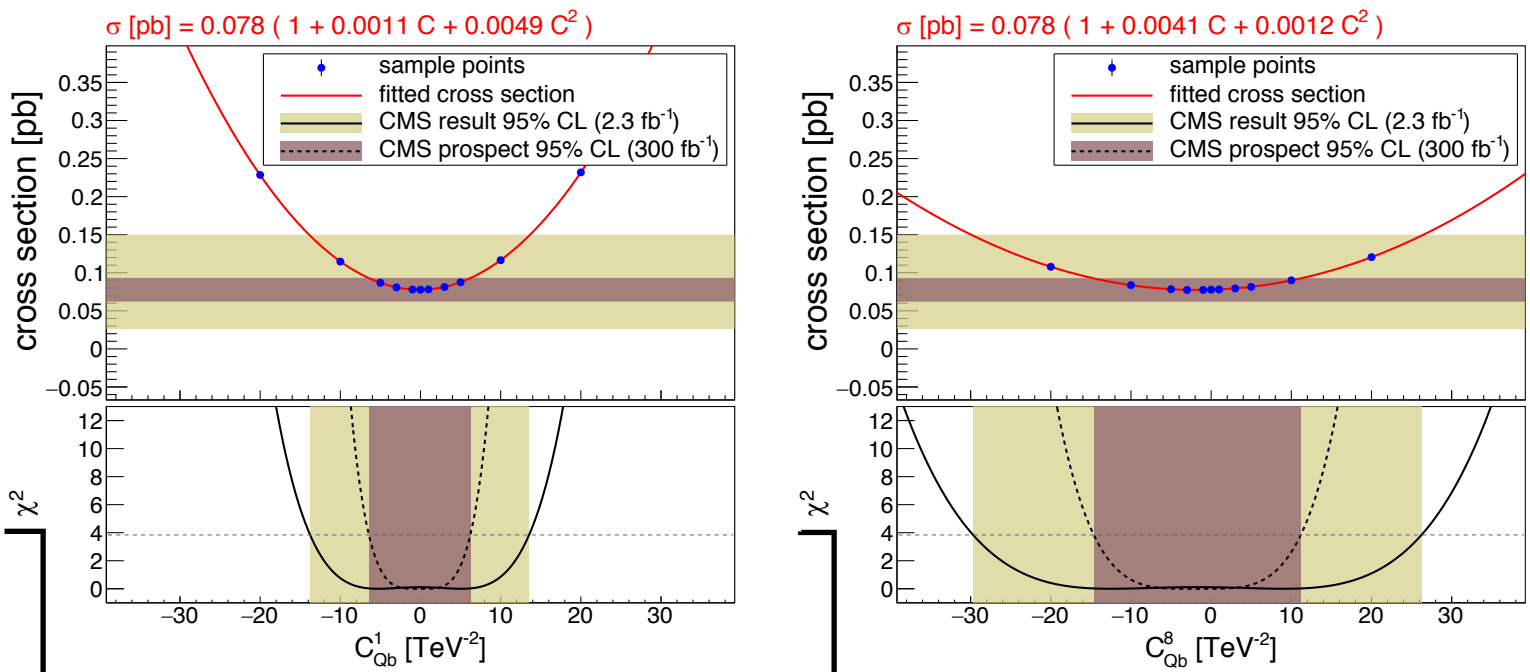
Cross section in the fiducial detector volume

CSM Collaboration, Measurements of $t\bar{t}$ cross sections in association with b jets and inclusive jets and their ratio using dilepton final states in pp collisions at $\sqrt{s}$ = 13 TeV, *Phys. Lett. B 776 (2018) 355*

Integrated luminosity = 2.3 fb^{-1}
Visible phase space definition:
$\sigma_{t\bar{t}b\bar{b},CMS} = 88 \pm 12(stat.) \pm 29(syst.)$ fb

Projections for 300 fb-1: scaled stat. unc. and fixed syst. unc. of 10%
measured xsec = prediction of MadGraph

$$\sigma_{fit} = \sigma_{SM}\left(1 + p_1 \cdot C_i + p_2 \cdot C_i^2\right)$$

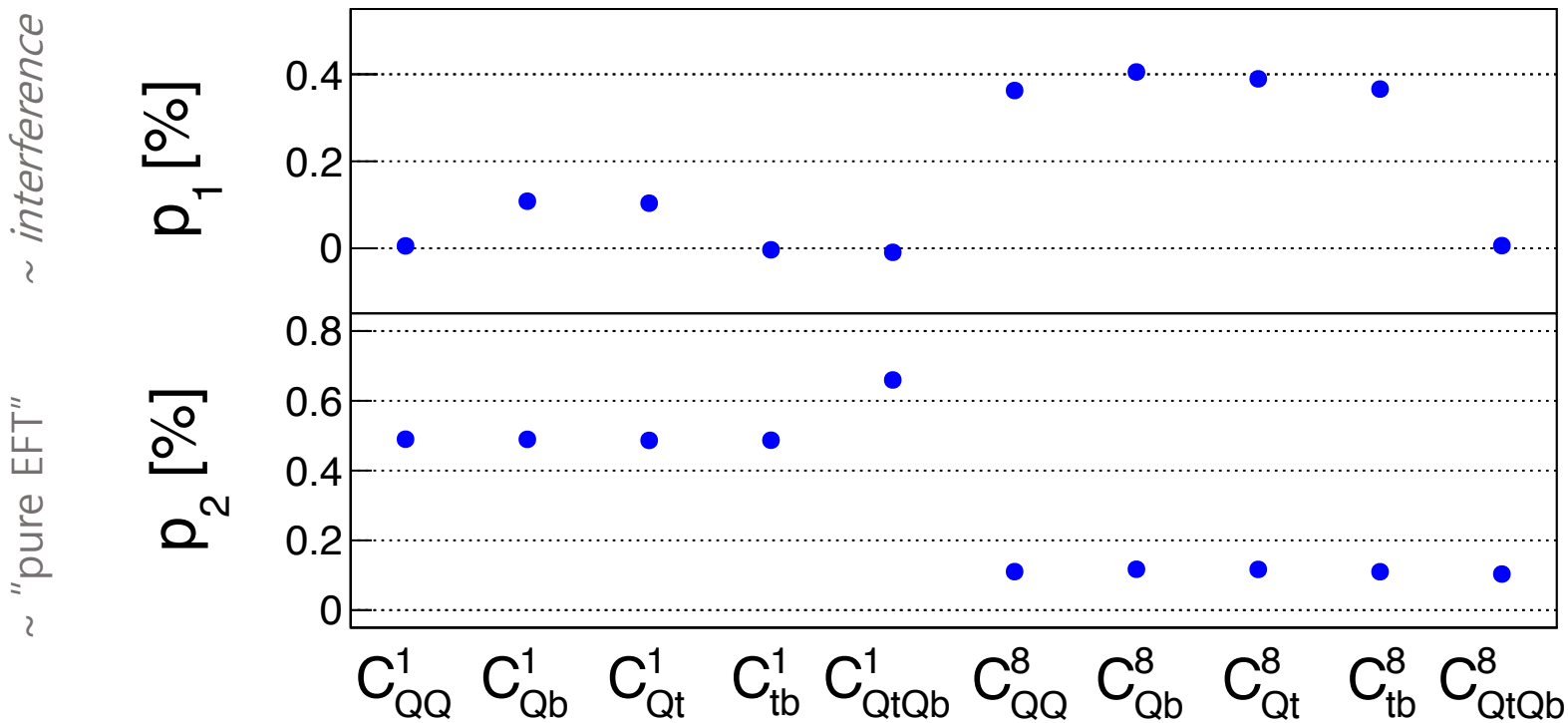


95% CL

$$\Delta\chi^2(C_i|p_1,p_2) = \chi^2(C_i|p_1,p_2) - \chi^2_{min} = \frac{\left(\sigma_{fit}(C_i|p_1,p_2) - \sigma_{obs}\right)^2}{\delta\sigma^2} - \chi^2_{min}$$

Cross section in the fiducial detector volume

$$\sigma_{fit} = \sigma_{SM}\left(1 + p_1 \cdot C_i + p_2 \cdot C_i^2\right)$$



Color singlet operators have small interference but larger squared order contributions

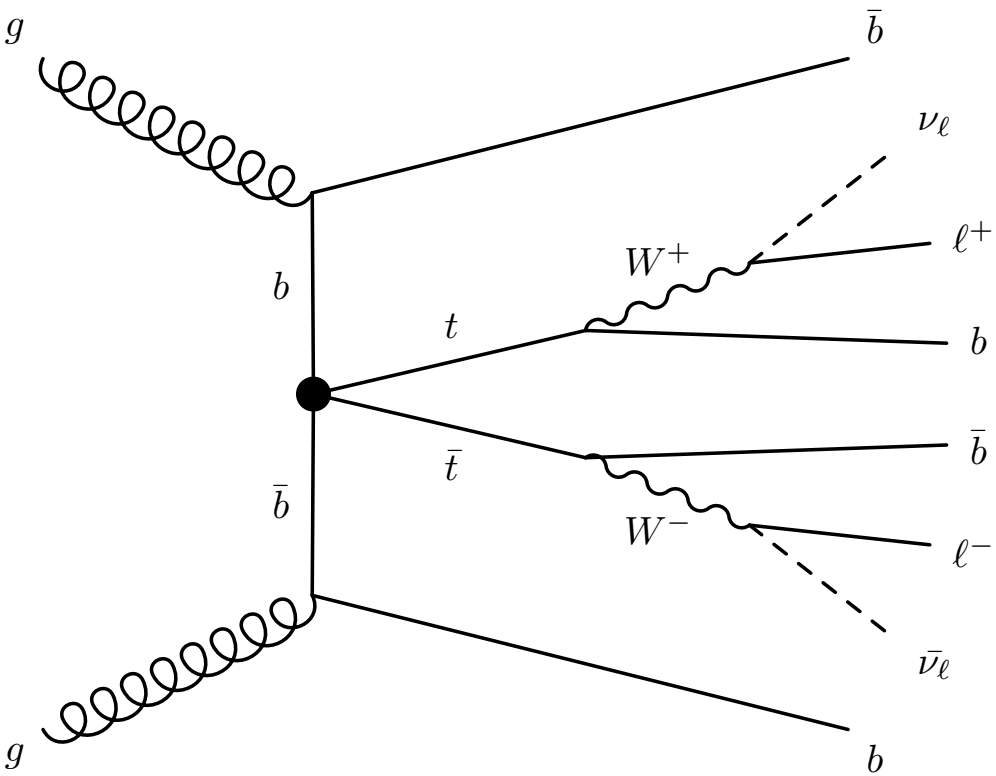
Color octet operators have larger interference (SM ~ gluon induced) but suppressed squared order contributions (color factor 2/9)

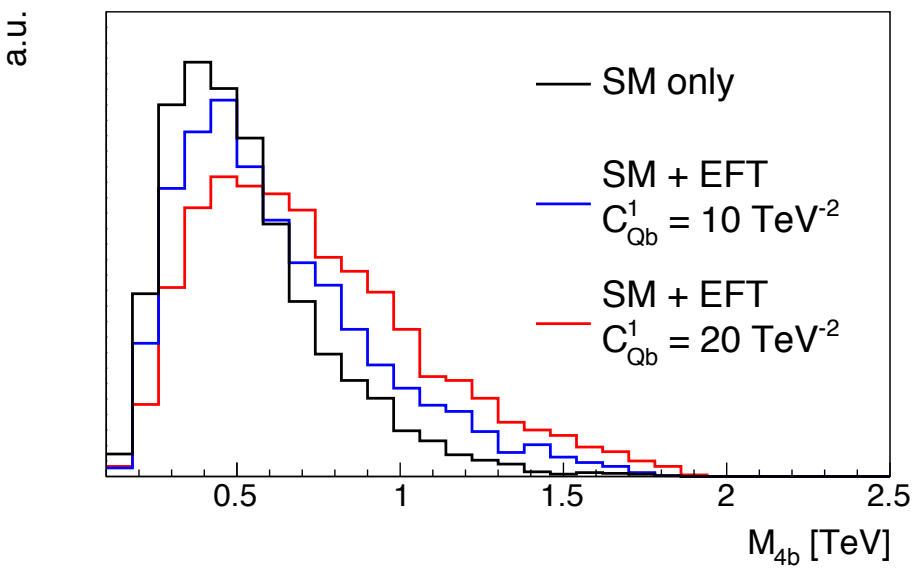
Tailoring the kinematical phase space

Step 1: move to the reconstructed phase space: **Dileptonic decays of the top quarks**

Step 2: identify quantities that are sensitive to the EFT operators (ΔR, M_{inv}, p_T, η) → **M_{4b}**

Step 3: Make a selection on this quantity and derive the effective cross section dependence





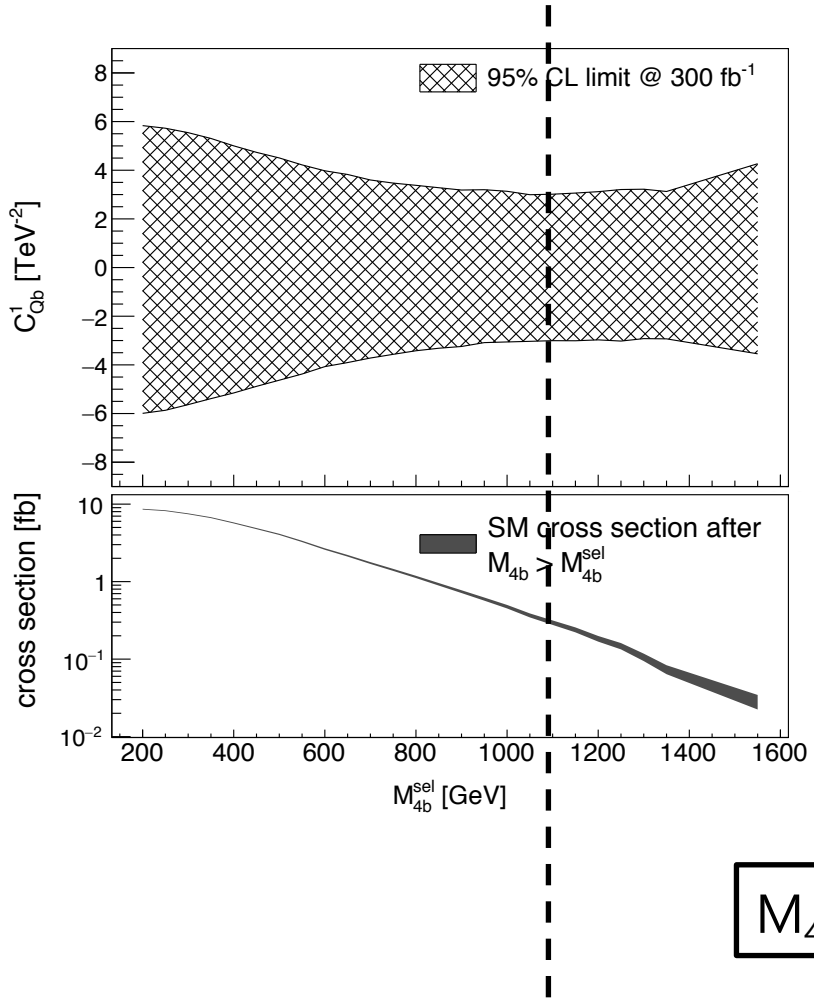
Tailoring the kinematical phase space

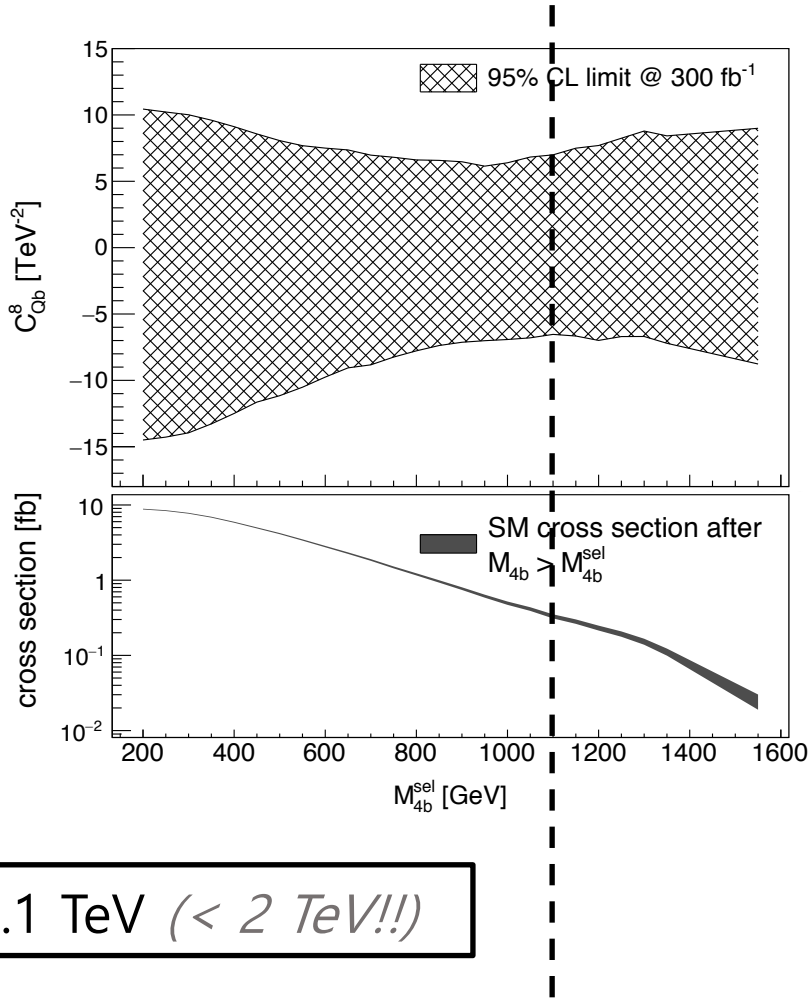
Question: What cut to choose on M4b?

Answer: The one that optimizes the sensitivity!

→ increase relative population of EFT contributions

→ without blowing up statistical uncertainty on the SM measurement

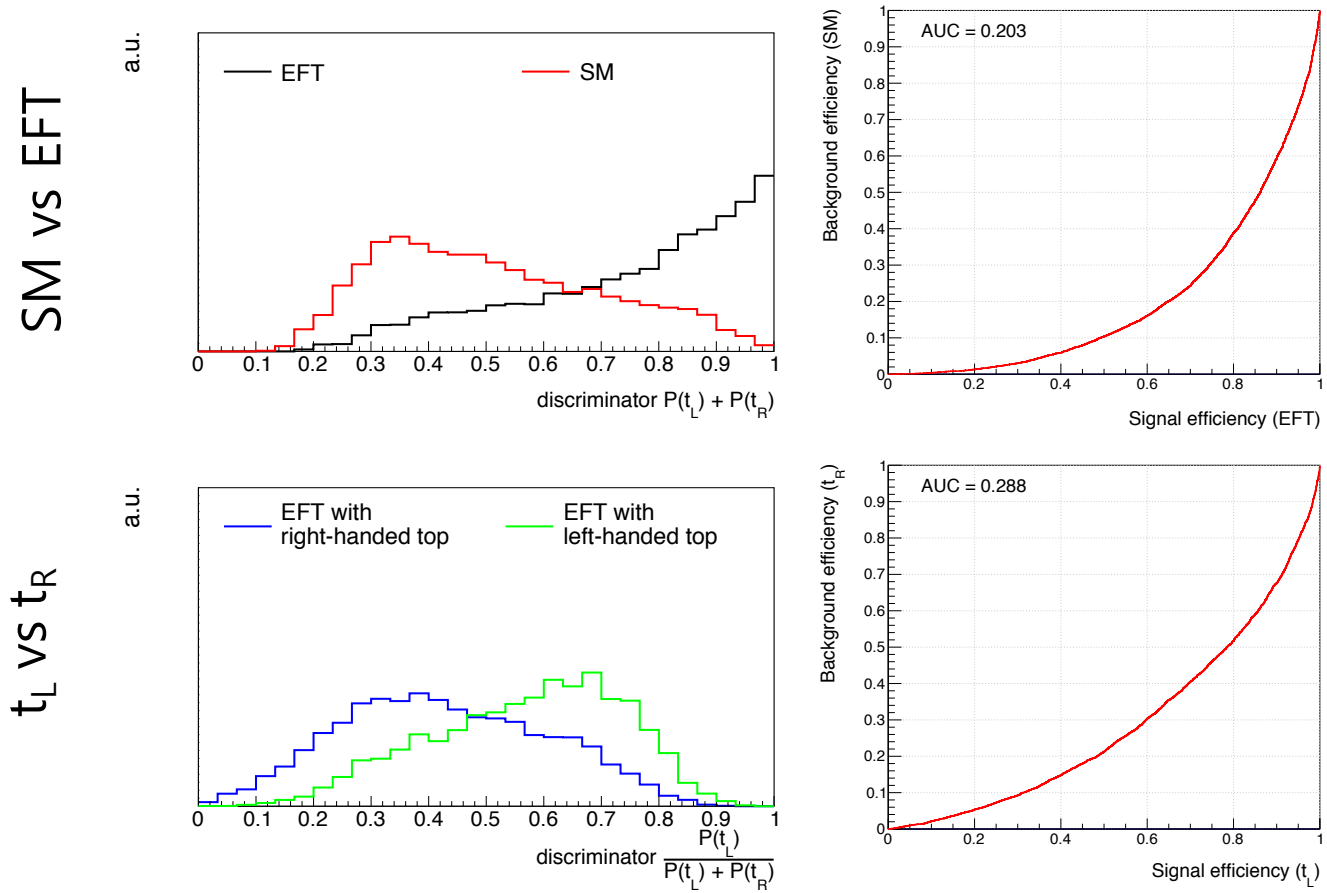




M_{4b} > 1.1 TeV *(< 2 TeV!!)*

Learning the effective operators

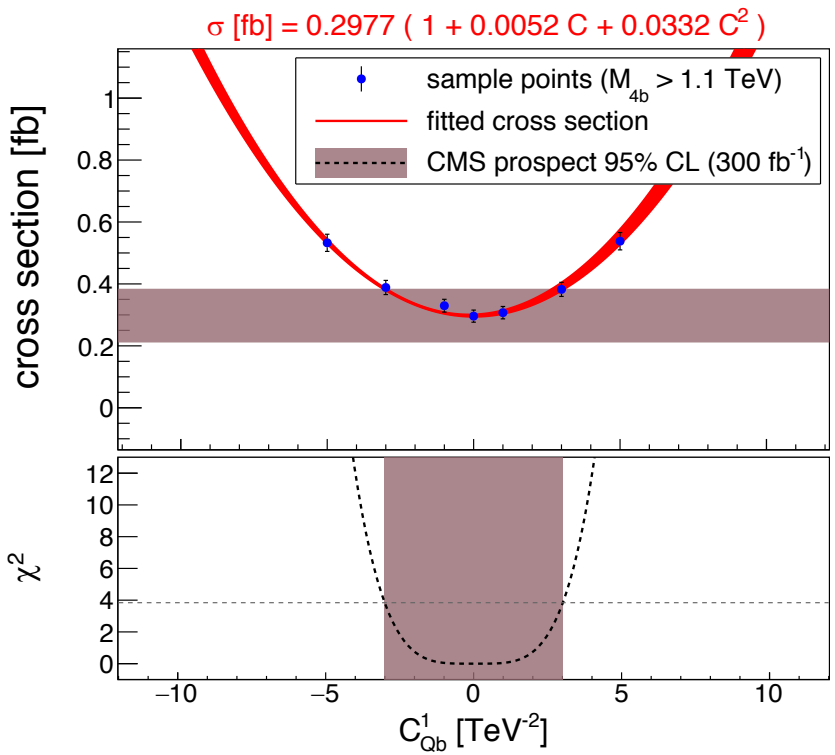
multiple operators

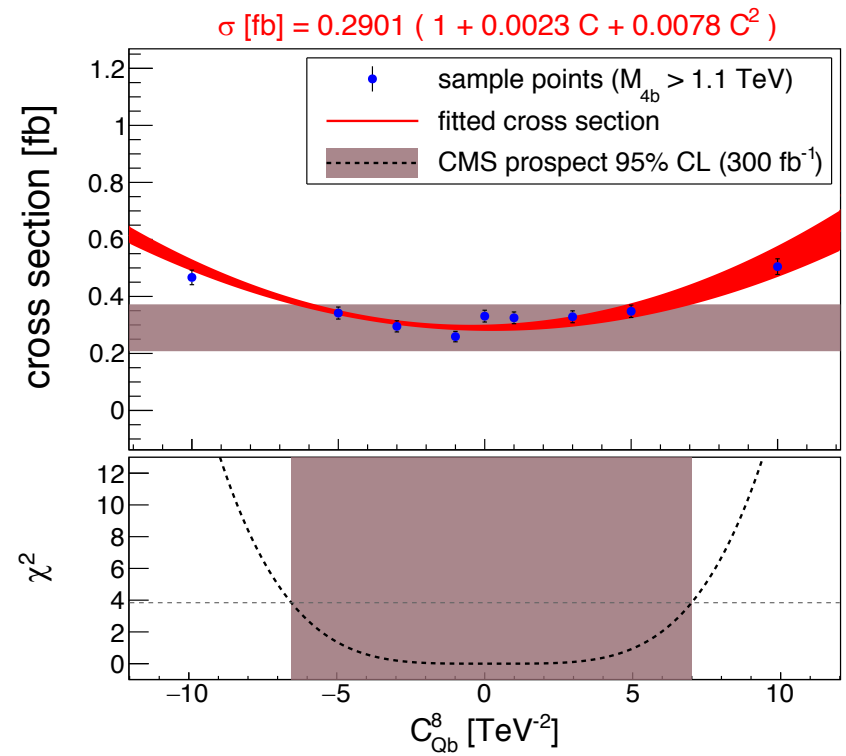


The NN has indeed learned to distinguish amongst t_L and t_R operators!

Tailoring the kinematical phase space

Prospects for 300 fb^{-1} after event reconstruction/selection and M_{4b} > 1.1 TeV





$C^1_{Qb} \in [-3, +3]$ TeV^{-2}
xsec: $C^1_{Qb} \in [-6, +6]$ TeV^{-2}

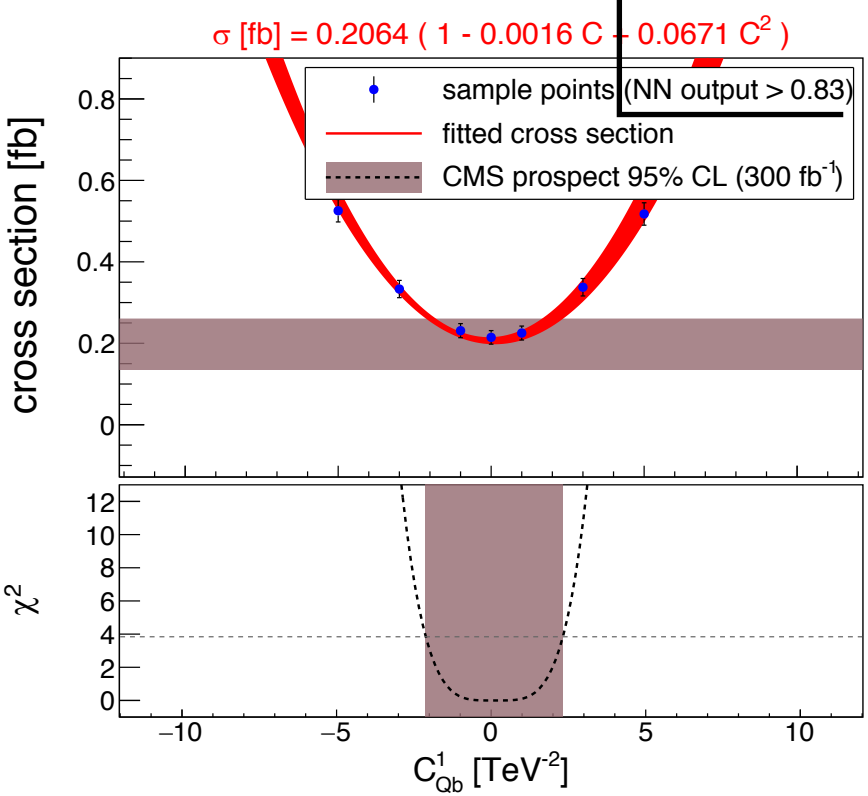
$C^8_{Qb} \in [-6.5, +7]$ TeV^{-2}
xsec: $C^8_{Qb} \in [-15, +10]$ TeV^{-2}

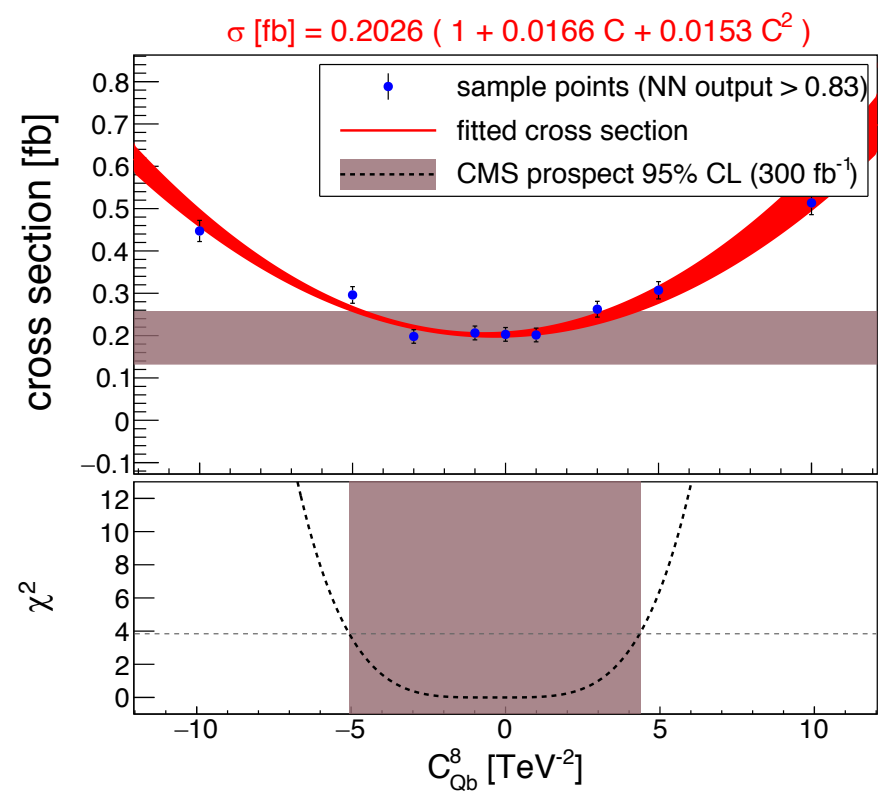
→ Improvement with a factor ~2!

Learning the effective operators
one operator at a time

	Desired Discrimination	Combined NN Output used for limits
only t_L operator	SM vs t_L	$\frac{P(t_L)}{P(t_L)+P(SM)}$
only t_R operator	SM vs t_R	$\frac{P(t_R)}{P(t_R)+P(SM)}$
including both t_L and t_R operators	EFT vs SM	$P(t_L)+P(t_R)$
	t_L vs t_R	$\frac{P(t_L)}{P(t_L)+P(t_R)}$

Once again the cut value is chosen to optimize the sensitivity





$C^1_{Qb} \in [-2.1, +2.3]$ TeV^{-2}
M_{4b}: $C^1_{Qb} \in [-3, +3]$ TeV^{-2}

$C^8_{Qb} \in [-5, +4.3]$ TeV^{-2}
M_{4b} : $C^8_{Qb} \in [-6.5, +7]$ TeV^{-2}

→ significant further improvement!

Learning the effective operators

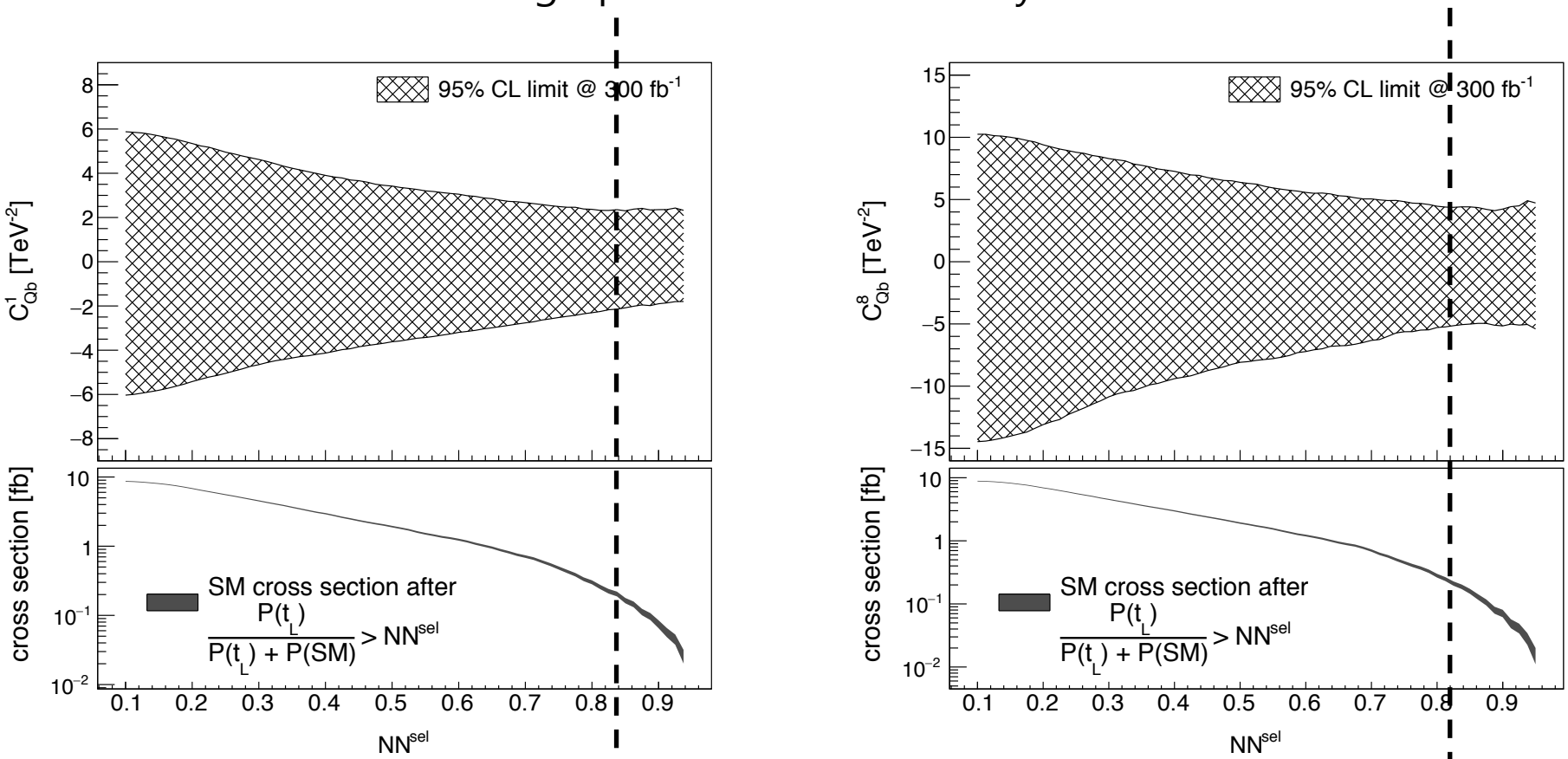
one operator at a time

Question: What cut to choose on the NN ouput?

Answer: The one that optimizes the sensitivity!

→ increase relative population of EFT contributions

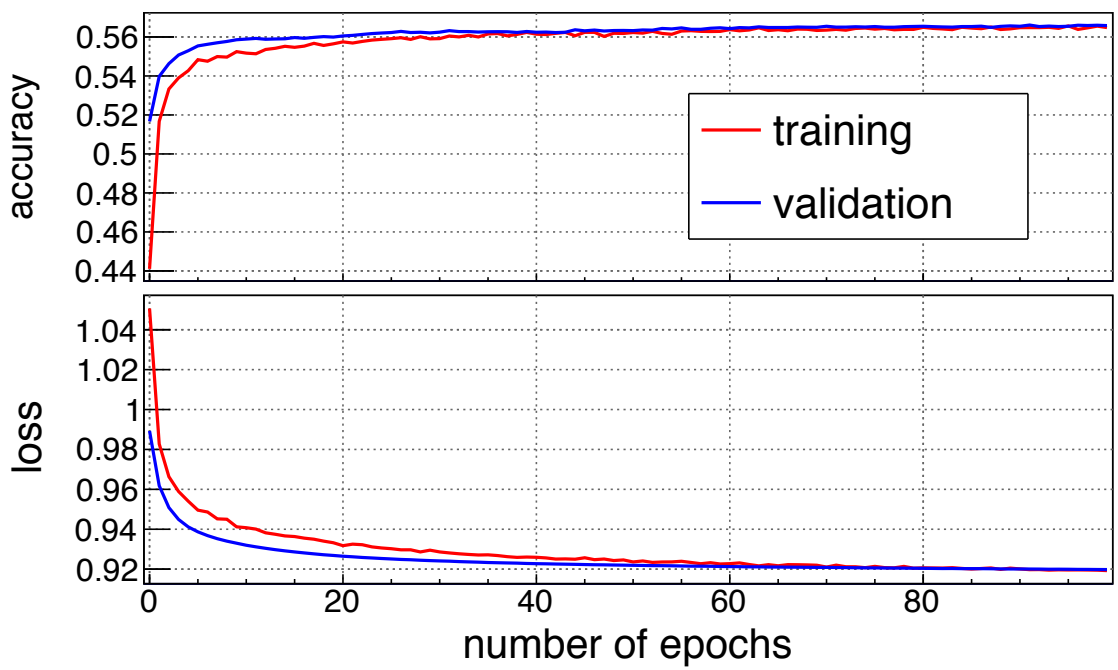
→ without blowing up statistical uncertainty on the SM measurement



NN output > 0.83

Backup: Neural Network training

- 18 inputs + RELU + 1 hidden layer (50 neurons) + RELU + Dropout (10%) + 3 outputs + SOFTMAX (sum=1)
- Mini-batches of size 128, training for 100 epochs
- Loss function: Categorical cross entropy
- Optimizer: Stochastic gradient descent
  - Initial learning rate = 0.005
  - Decay = 10^{-6}
  - Nestrov momentum = 0.8



Variables used in the network

ΔR	m_{inv}	p_T
$\Delta R(\ell_1,\ell_2)$	$m_{inv}(\ell_1,\ell_2)$	$p_T(\ell_1)$
$\Delta R(b_1,b_2)$	$m_{inv}(b_1,b_2)$	$p_T(\ell_2)$
$\Delta R(b_1,\ell_2)$	$m_{inv}(b_1,\ell_2)$	$p_T(b_1)$
$\Delta R(b_2,\ell_1)$	$m_{inv}(b_2,\ell_1)$	$p_T(b_2)$
$\Delta R(add_1,add_2)$	$m_{inv}(add_1,add_2)$	$p_T(add_1)$
	$m_{inv}(b_1,b_2,add_1,add_2)$	$p_T(add_2)$
	$m_{inv}(\ell_1,\ell_2,b_1,b_2,add_1,add_2)$	

Outlook

- Fully marginalized limits when more precise measurements become available
- Method is generic and can be applied to other topologies / final states!
- Increased complexity of the network (Deep learning) or more advanced machine learning techniques may result in better sensitivity.
- Question for the future: How much can we push these algorithms to distinguish different EFT operators.
  - We demonstrated a distinction between t_L and t_R operators
  - Distinguish color singlet operators from color octet ones would be possible if one includes interference effects during the training phase!
    (becomes dependent on the value of the Wilson coefficient
    → Parametrized learning approach?)
  - Can you (ideally) distinguish each individual operator or are some of them indistinguishable?