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

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fwo Opening new horizons

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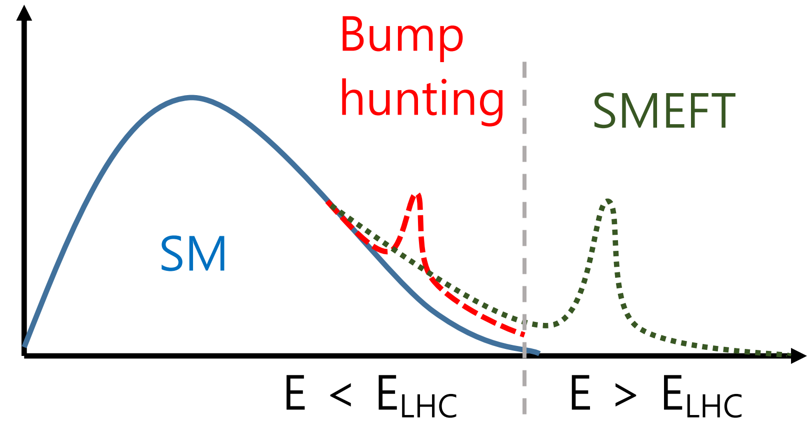
Contents

The Standard Model Effective Field Theory

Lack of direct evidence for BSM physics at the LHC
$\longrightarrow$ Standard Model Effective Field Theory (SMEFT):

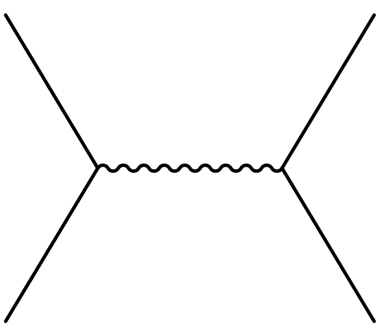
- model-independent interpretation
- New physics at high energy scales
- Heightened energy dependence and modified kinematics



Extend SM Lagrangian up to dim. 6:

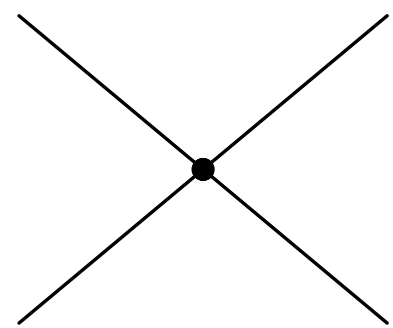
(→ Leading B & L conserving contributions)

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



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

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



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

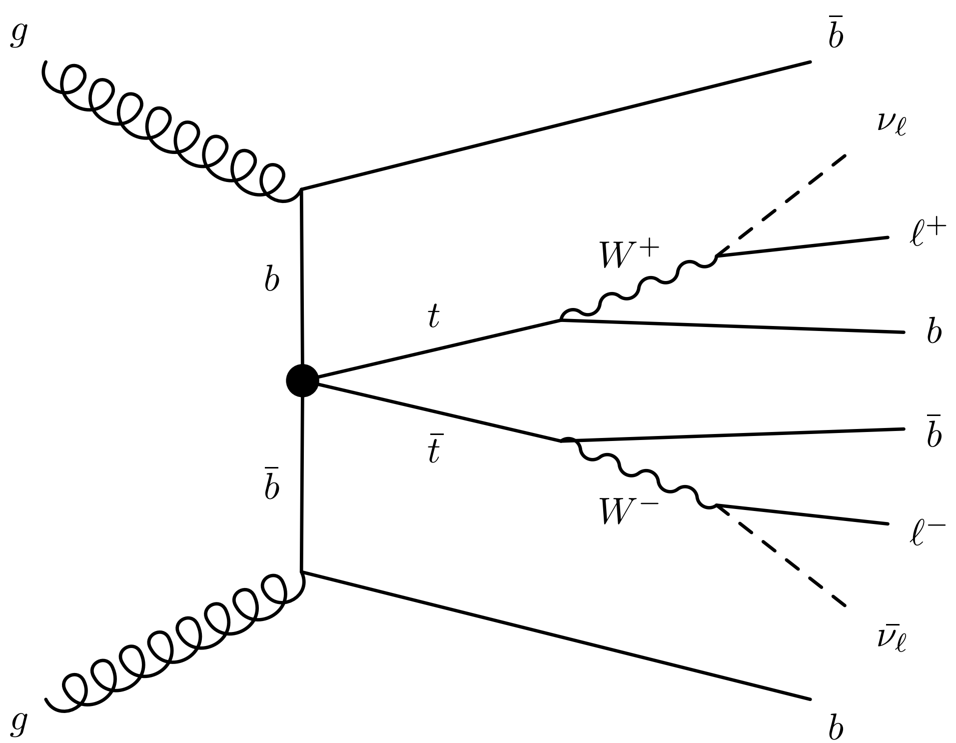
$t\bar{t}b\bar{b}$ in SMEFT
four-heavy-quark operators

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

Some operators can be constrained by four top as well

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

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

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

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)

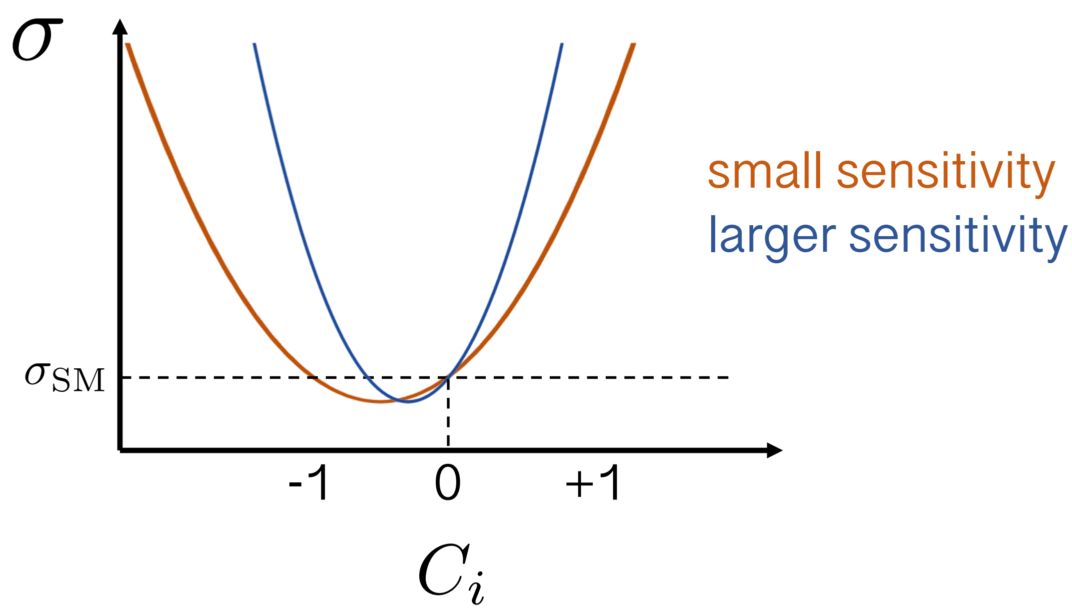
The name of the game:
Increasing sensitivity to SMEFT operators

interference — quadratic (pure EFT)

$$\sigma = \sigma_{SM} + \sum_i \frac{C_i}{\Lambda^2}\,\tilde{\sigma}_i + \sum_{i,j} \frac{C_i\,C_j}{\Lambda^4}\,\tilde{\delta}_{i,j}$$

<u>1 operator:</u>

$$\sigma = \sigma_{\mathrm{SM}} + \mathrm{p}_1 \cdot \frac{C_i}{\Lambda^2} + \mathrm{p}_2 \cdot \frac{C_i^2}{\Lambda^4}$$



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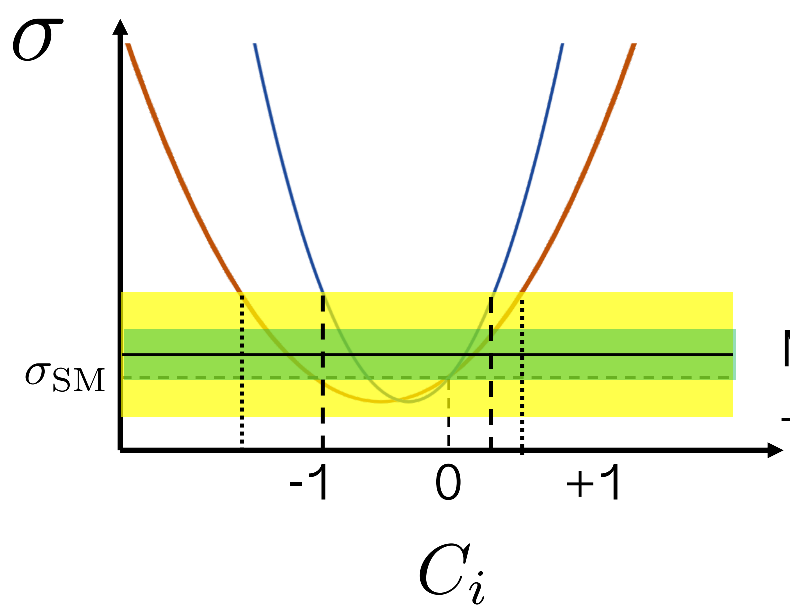
<u>1 operator:</u> $\sigma = \sigma_{\mathrm{SM}} + \mathrm{p}_1 \cdot \frac{C_i}{\Lambda^2} + \mathrm{p}_2 \cdot \frac{C_i^2}{\Lambda^4}$



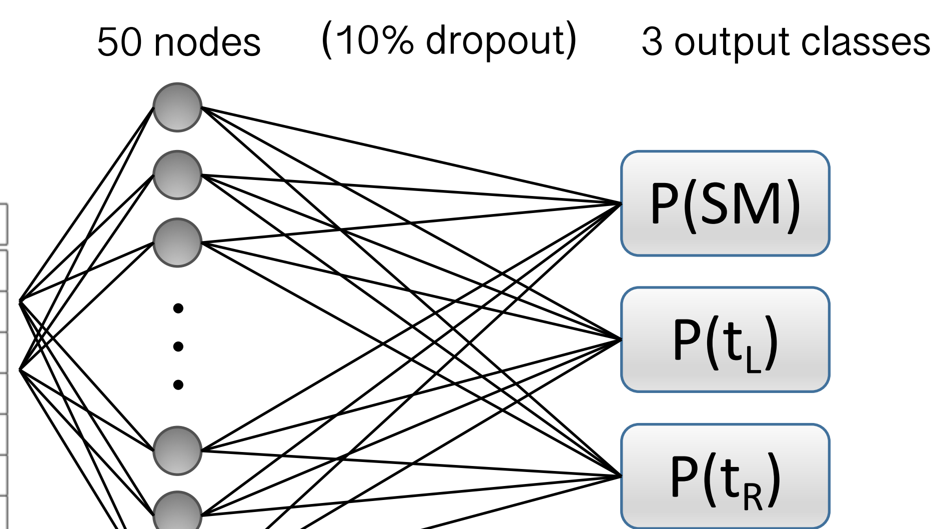
Measurement
→ limits on Wilson Coeff.

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)!

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
combining NN outputs

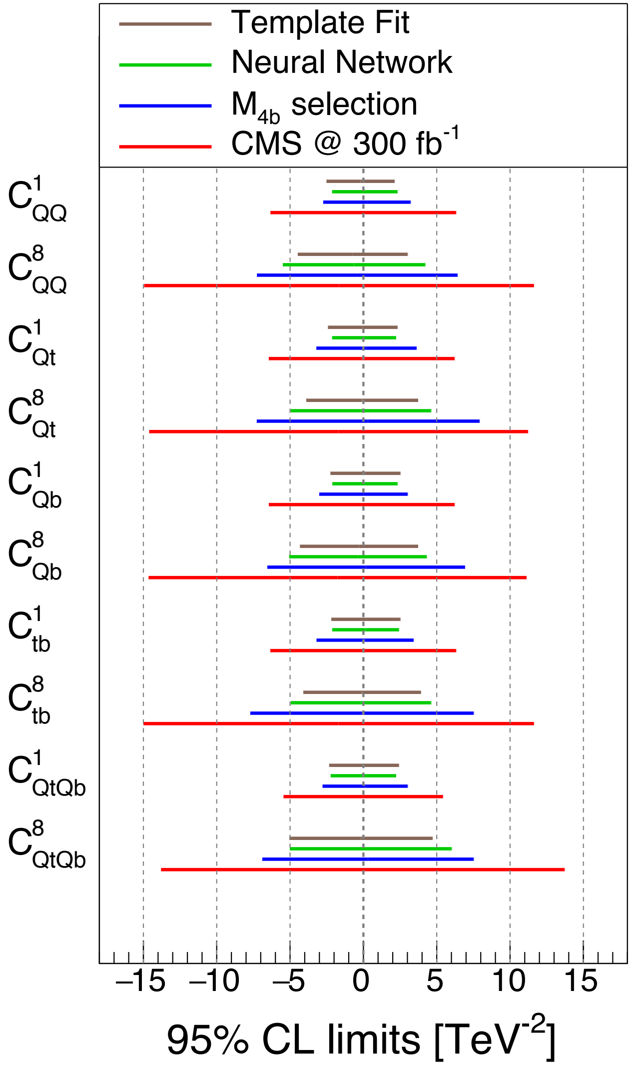
	Desired Discrimination	Combined NN Output used for limits
only t_L operator	SM vs t_L	$\frac{P(t_L)}{P(t_L)+P(SM)}$
only t_R operator	SM vs t_R	$\frac{P(t_R)}{P(t_R)+P(SM)}$
including both t_L and t_R operators	EFT vs SM	$P(t_L) + P(t_R)$
	t_L vs t_R	$\frac{P(t_L)}{P(t_L)+P(t_R)}$

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

Limits on individual operators
Sensitivity study

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



Factor ~2 improvement from fiducial phase space definition to EFT-enriched NN selection!

Contributions from multiple operators
one LH and one RH top-quark operator

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

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

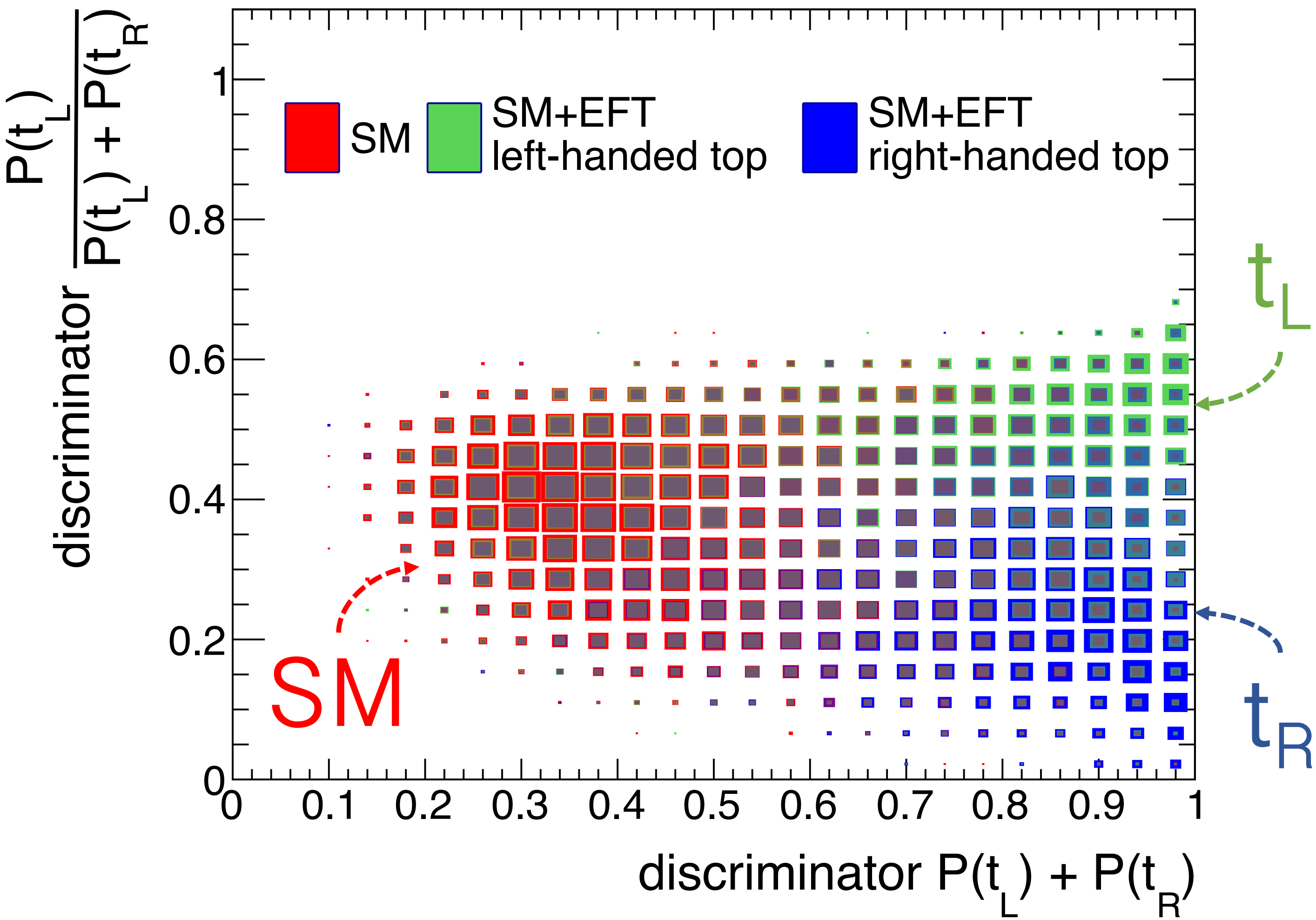
Contributions from multiple operators

one LH and one RH top-quark operator

2-dim phase space of NN outputs

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

y-axis: t_L vs t_R

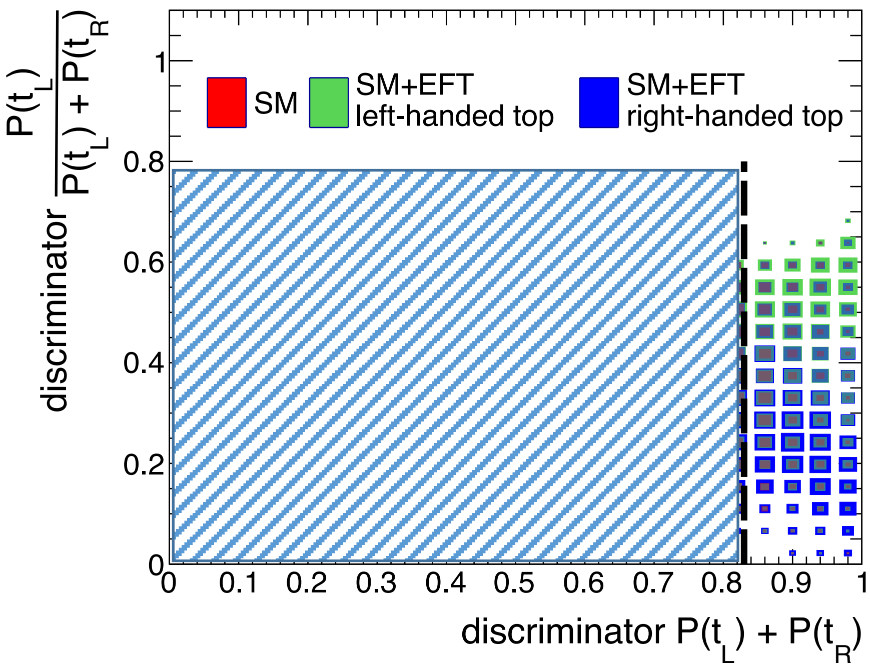


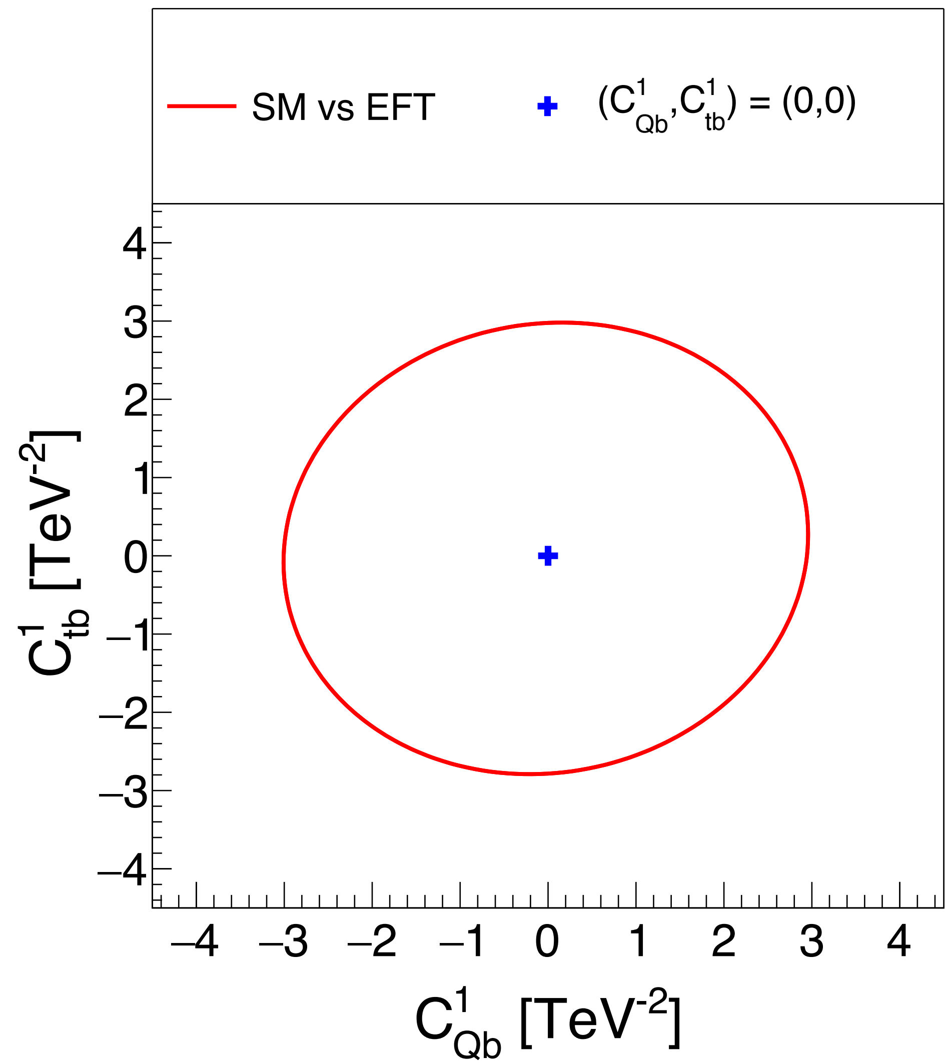
Contributions from multiple operators

SM-hypothesis → limits

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

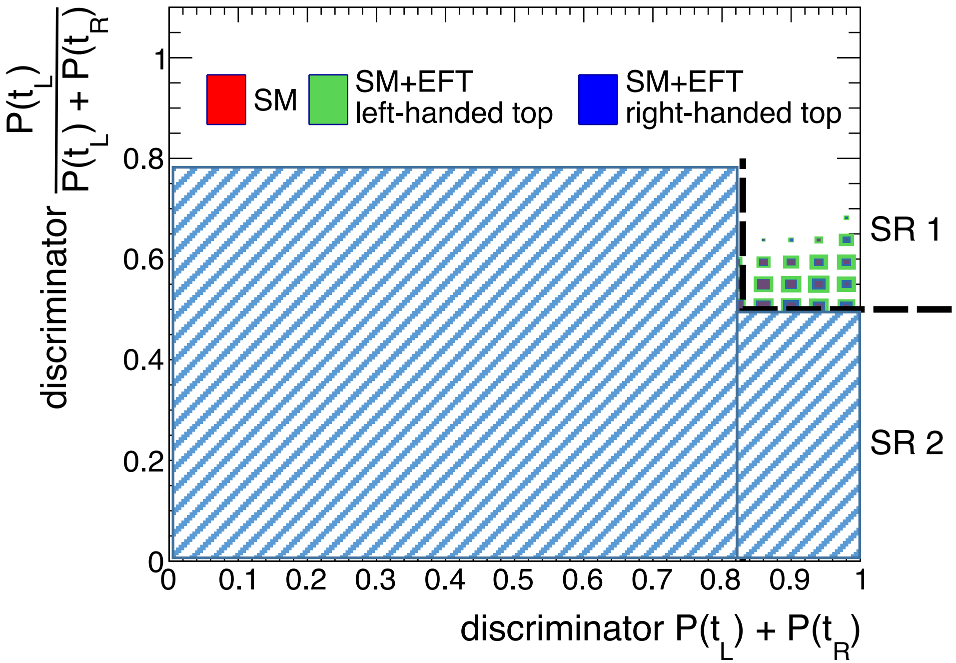
→ Assume an observation of the SM: $(C^1_{tb}, C^1_{Qb}) = (0,0)$

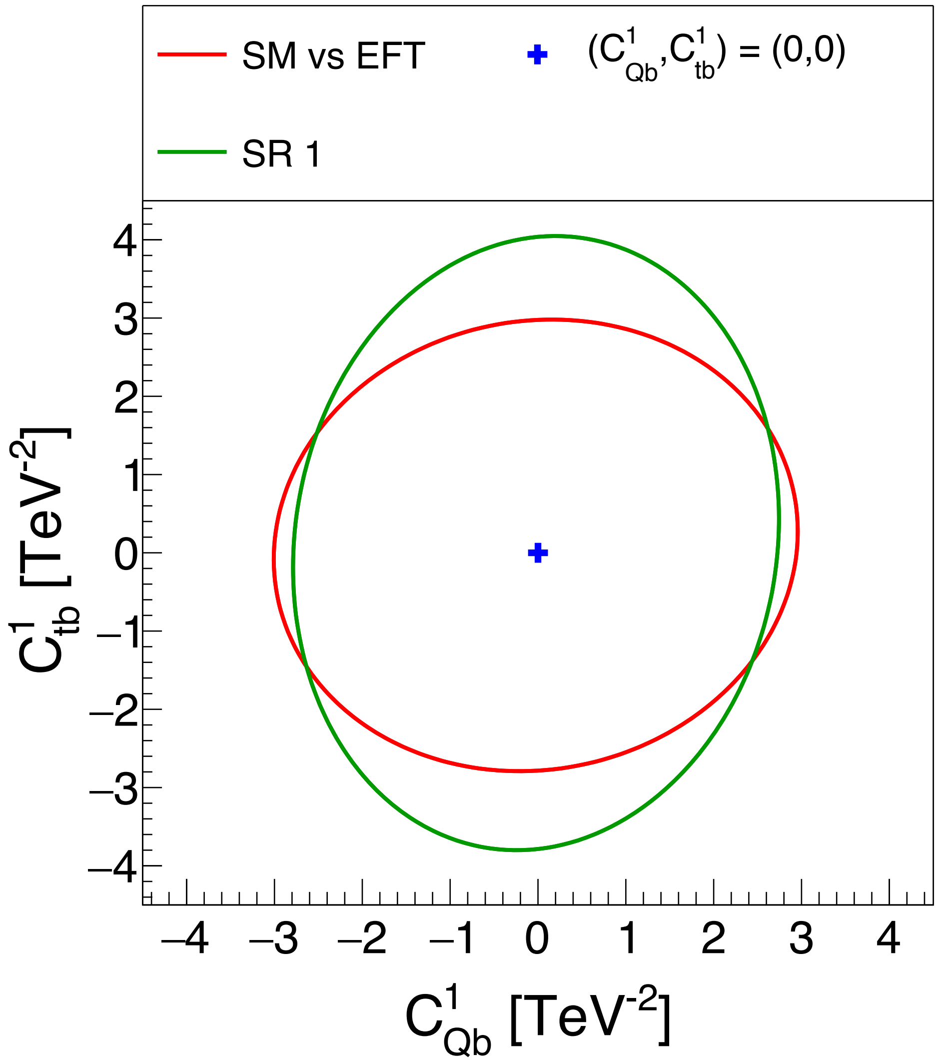




Contributions from multiple operators
SM-hypothesis → limits

Case-study: Consider two non-zero Wilson coefficients: C_{tb}^{1} and C_{Qb}^{1}
→ Assume an observation of the SM: $(C_{tb}^{1}, C_{Qb}^{1}) = (0,0)$





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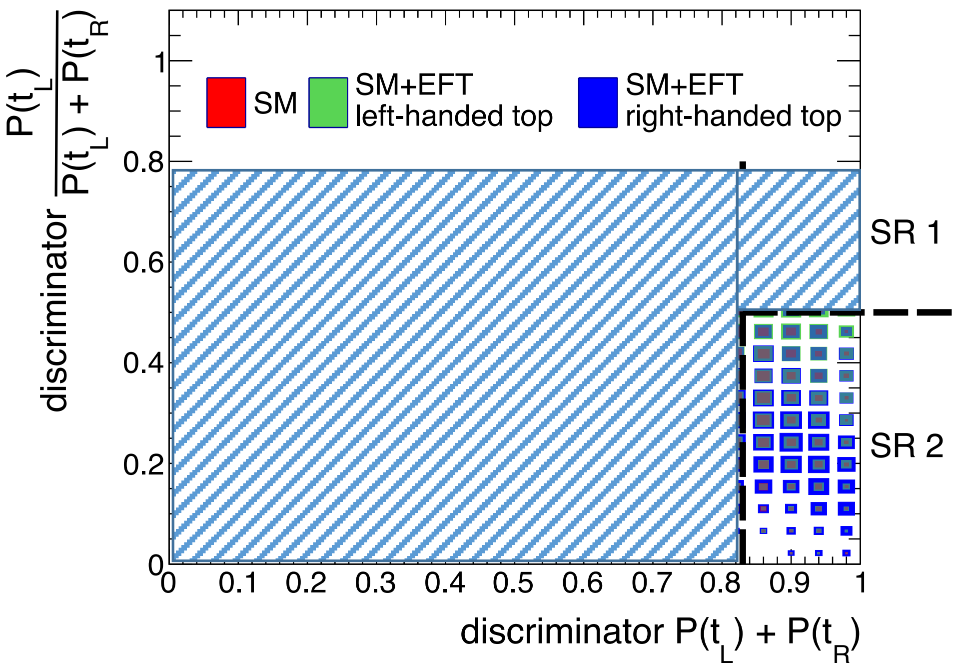

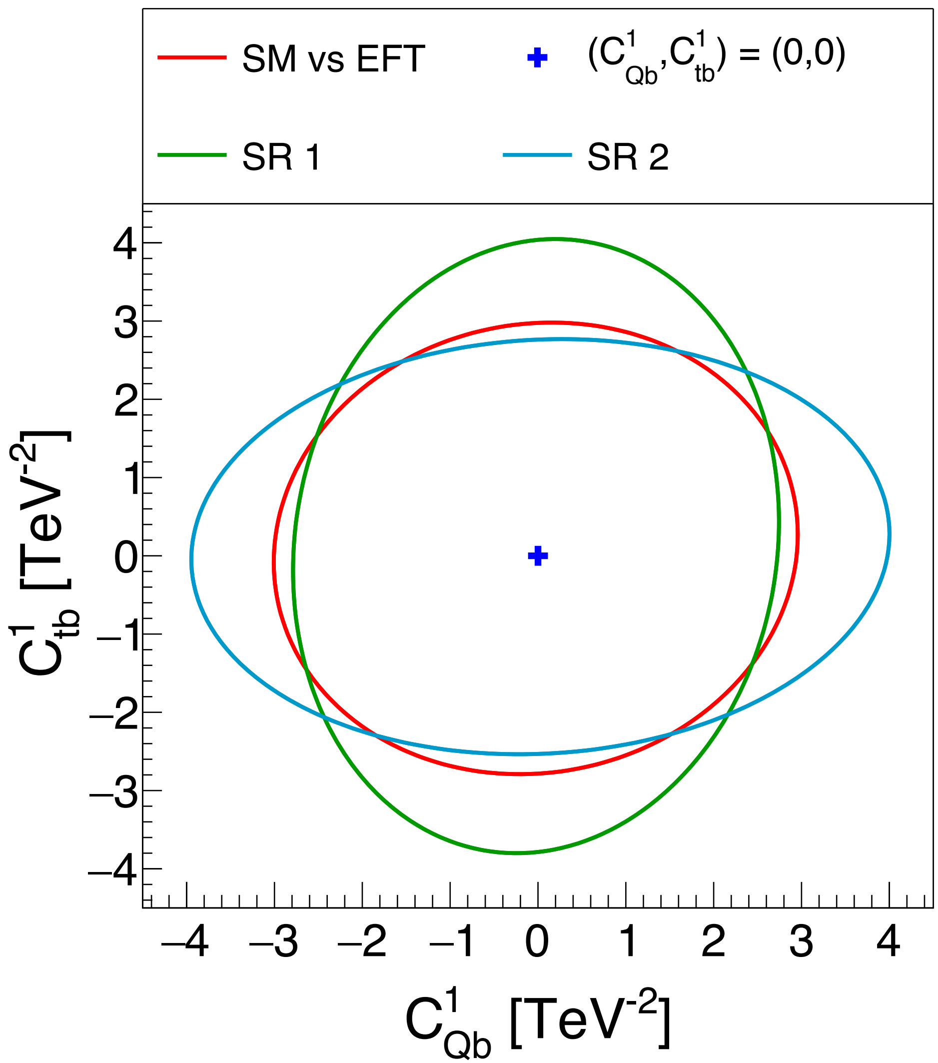

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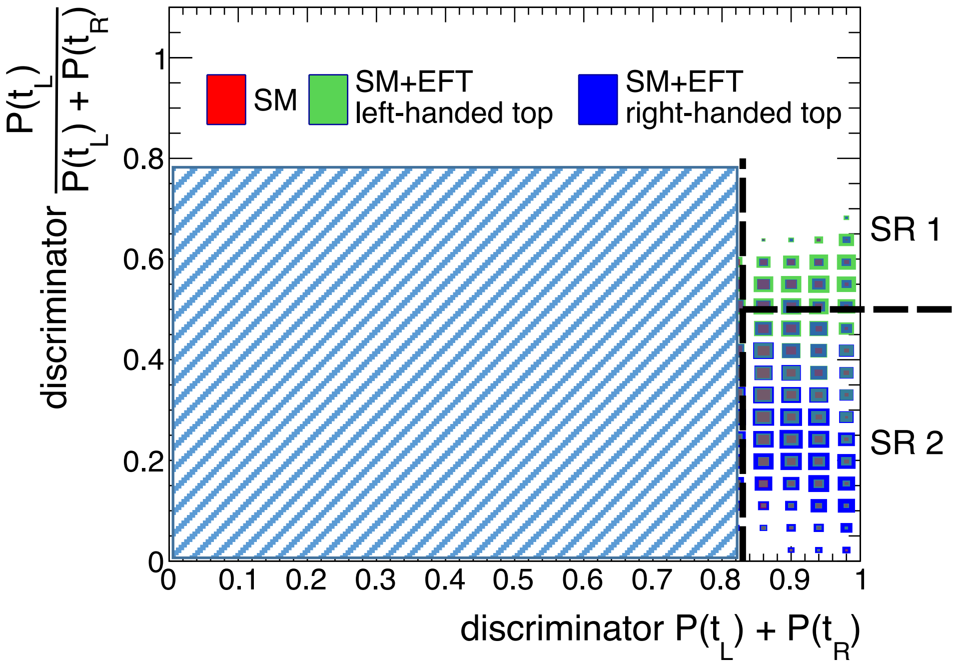

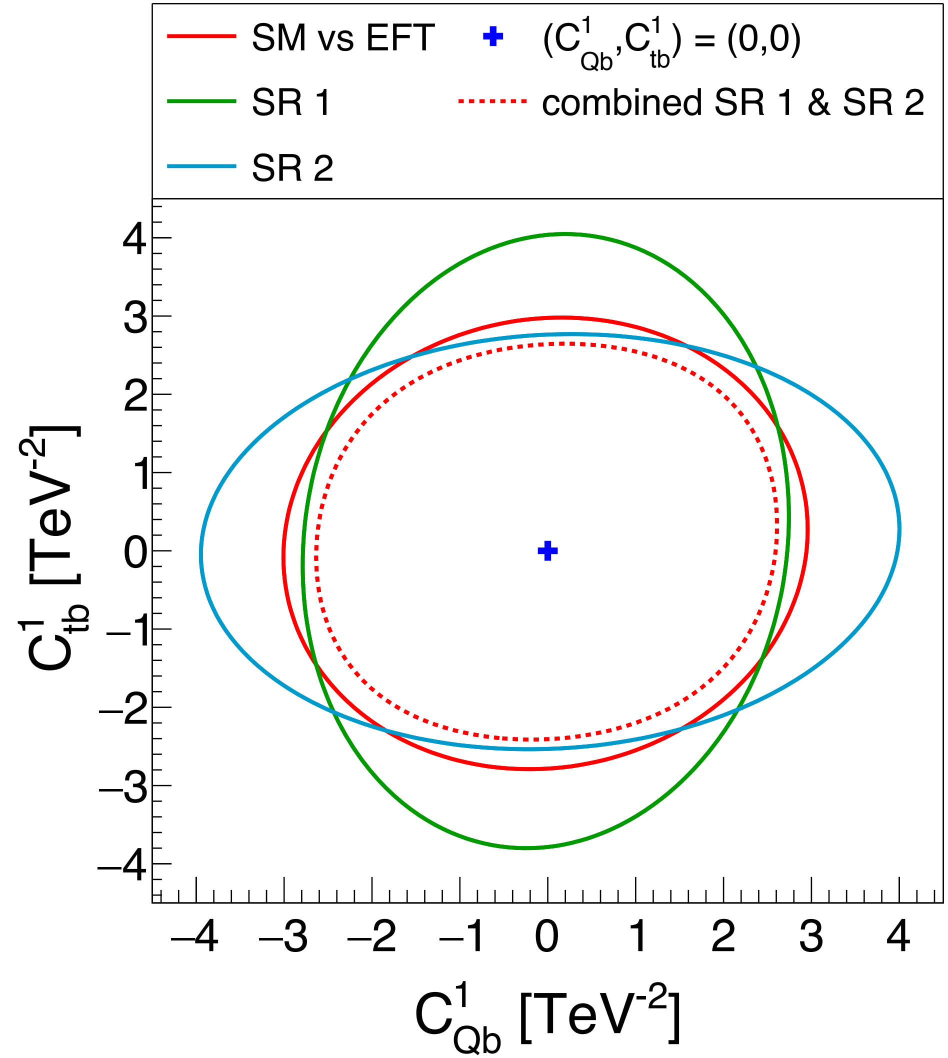

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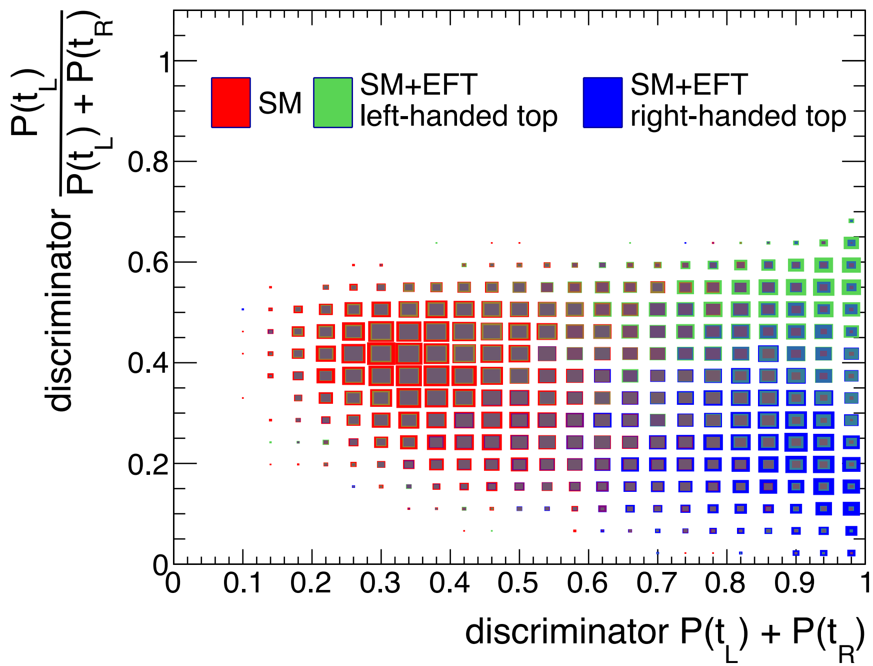
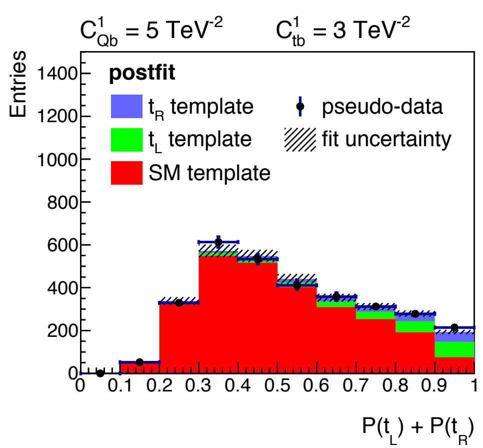
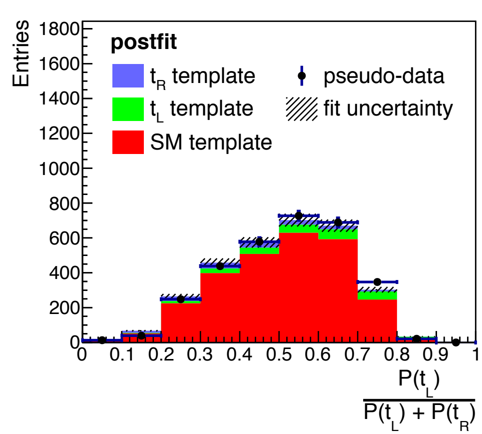
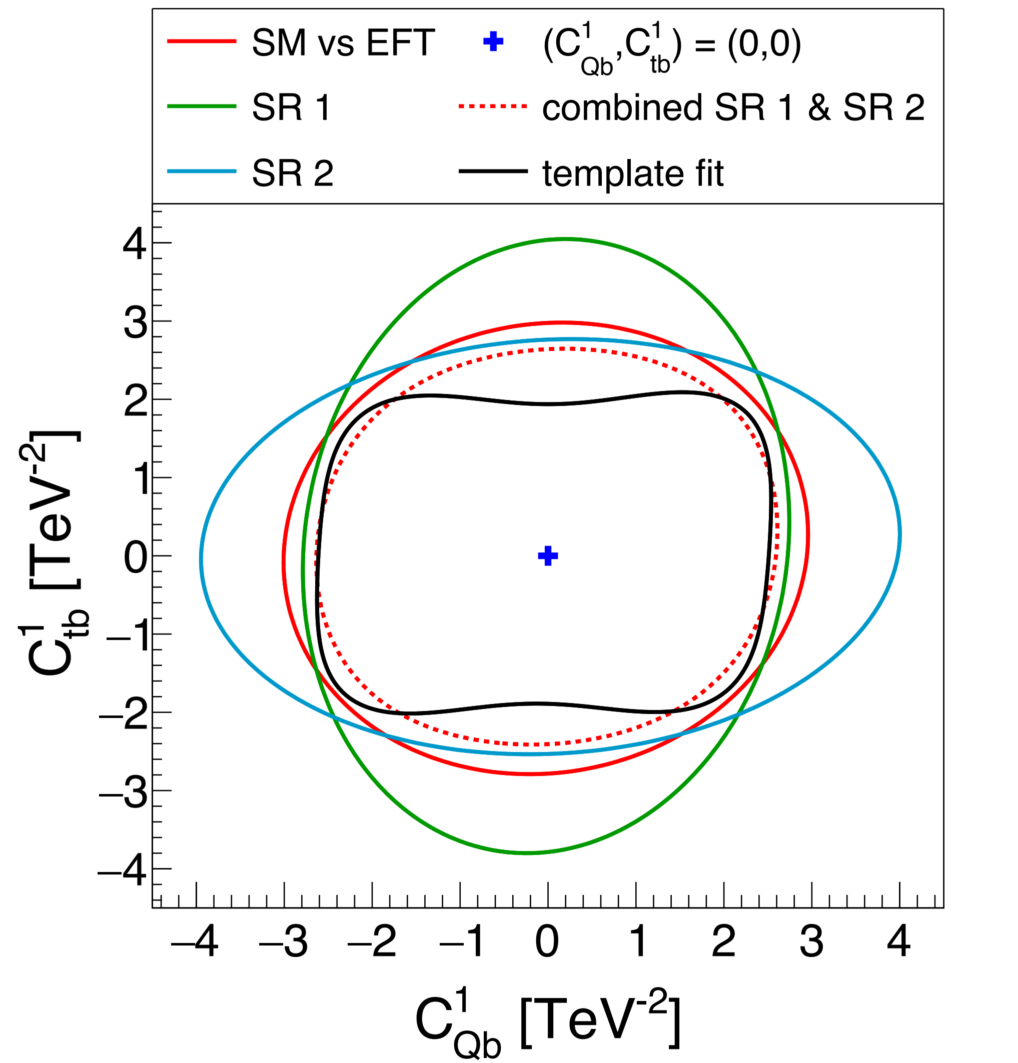




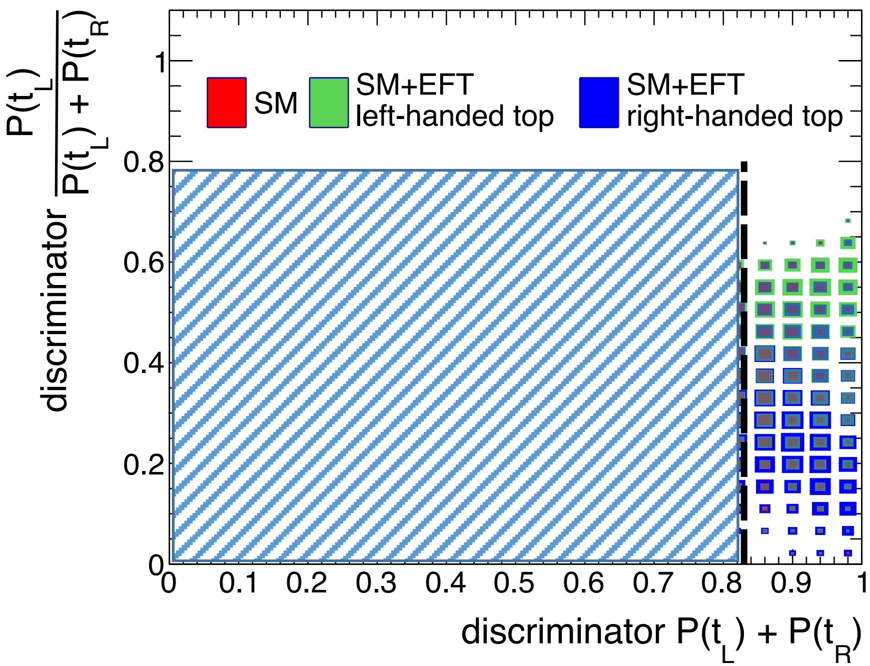


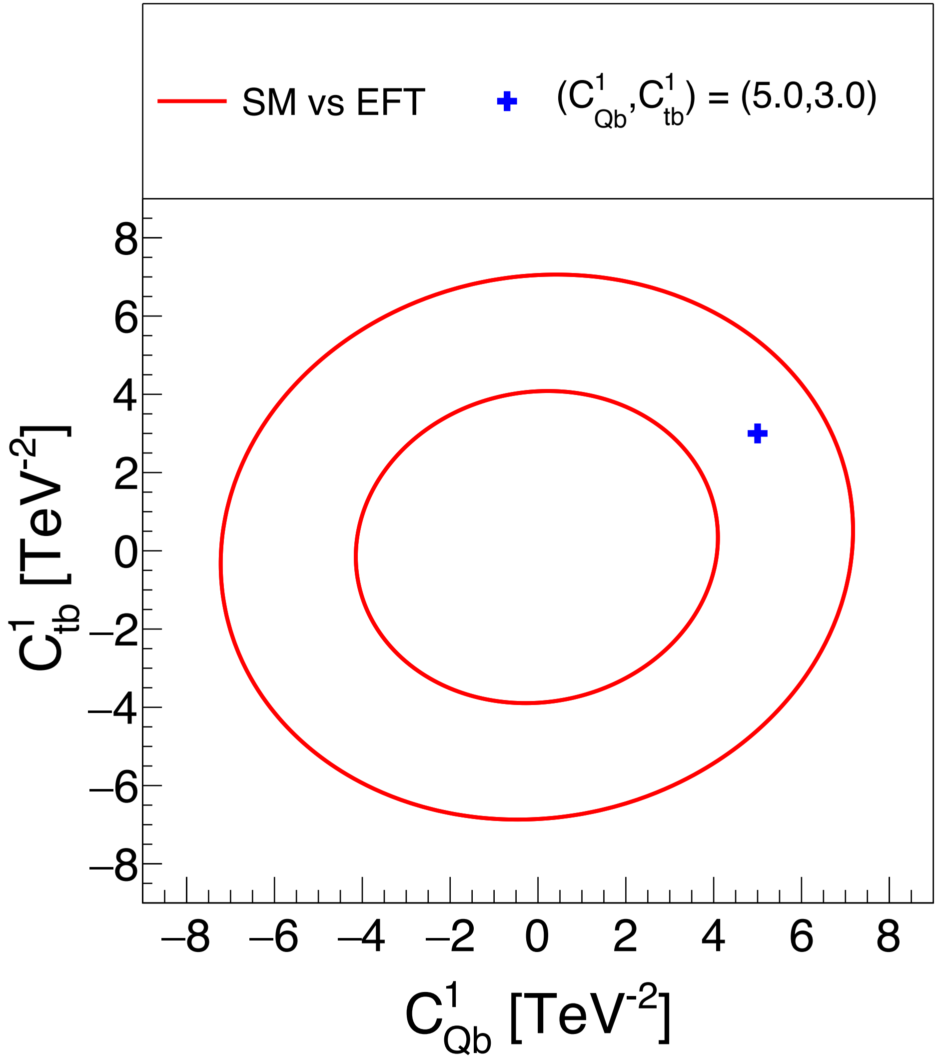


Contributions from multiple operators
SMEFT-hypothesis → observation?

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

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





Contributions from multiple operators
SMEFT-hypothesis → observation?

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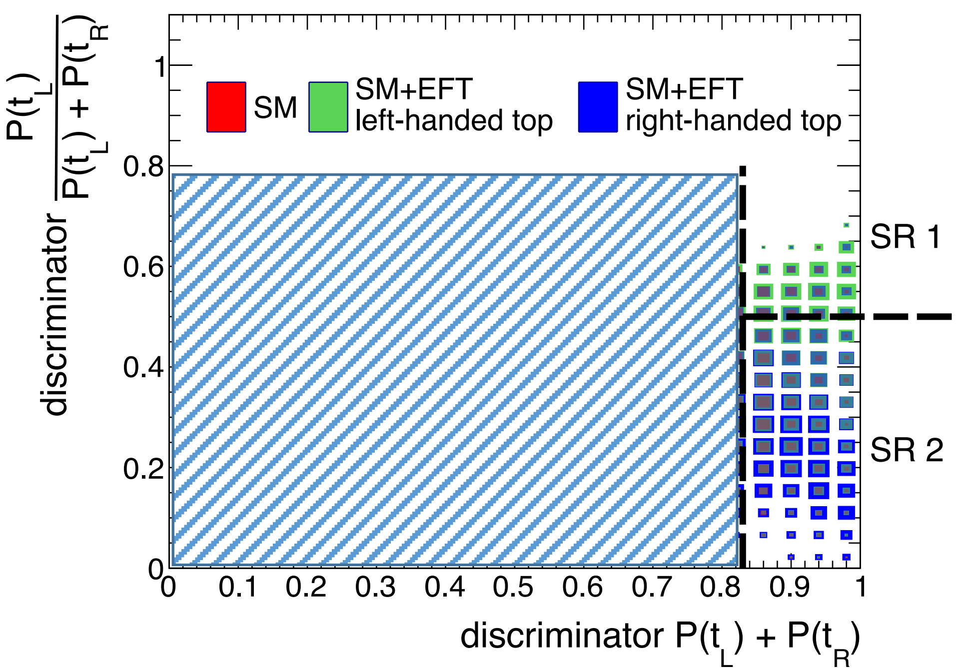
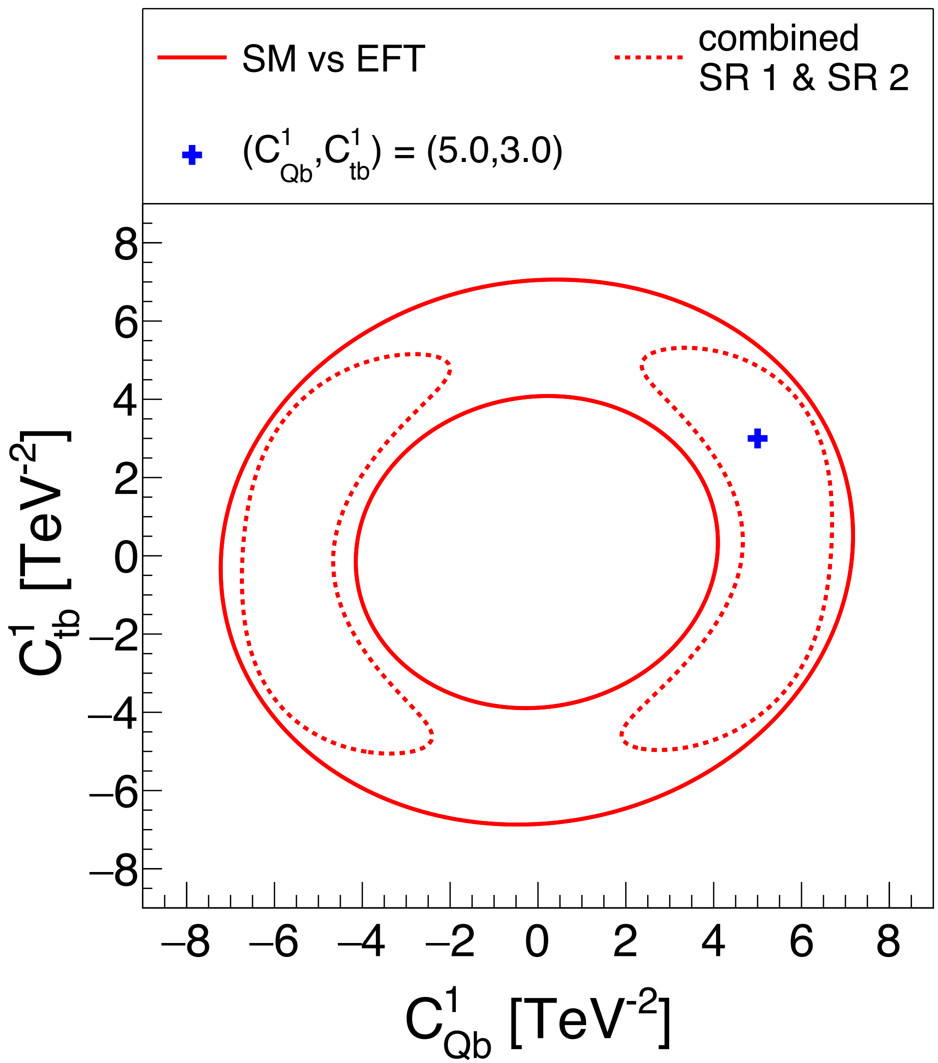
→ Assume an observation of EFT signal: $(C^1_{tb}, C^1_{Qb}) = (5{,}3)$





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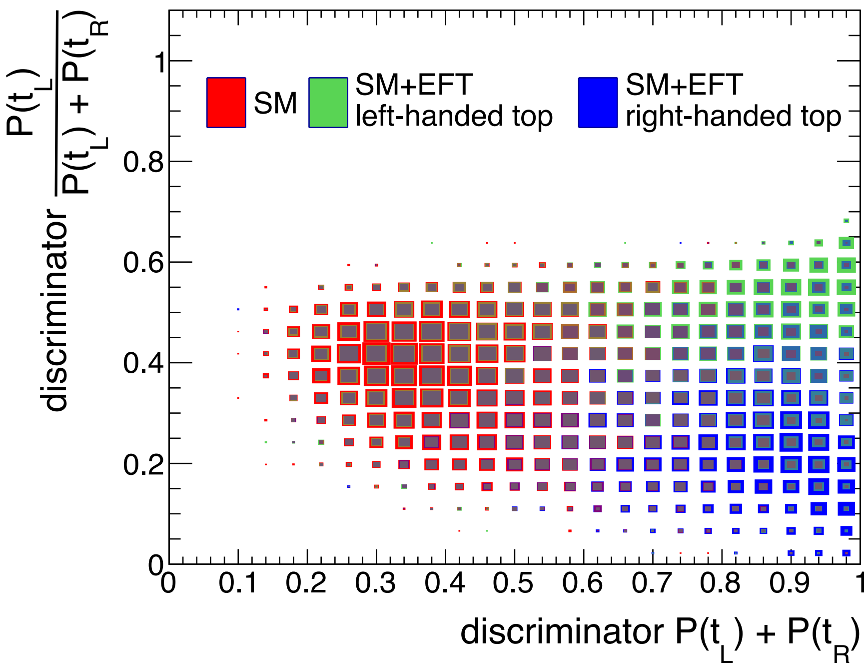
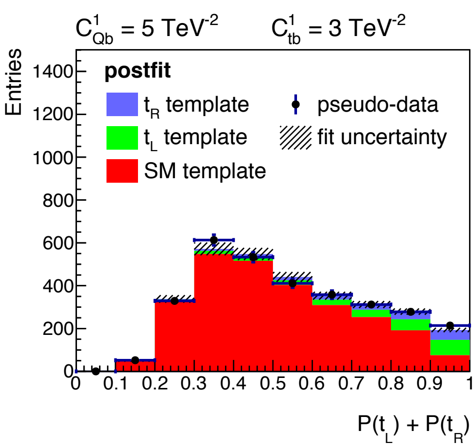
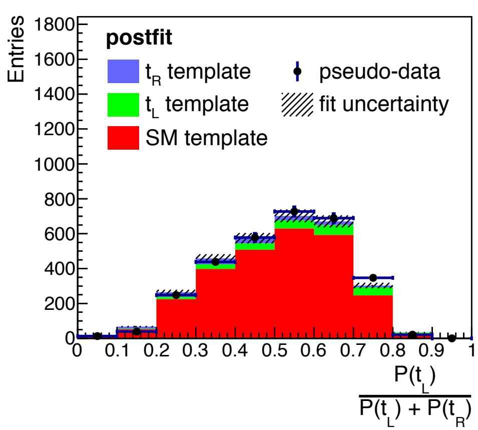
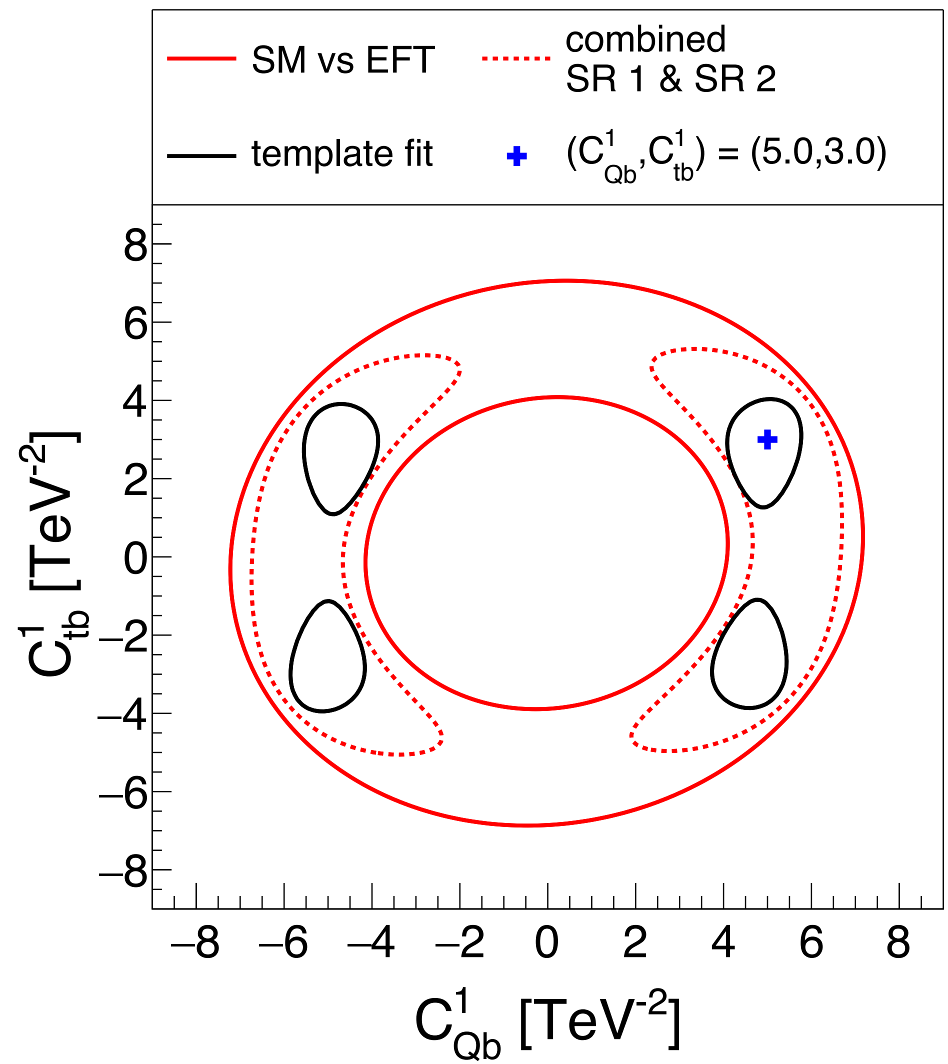








Summary

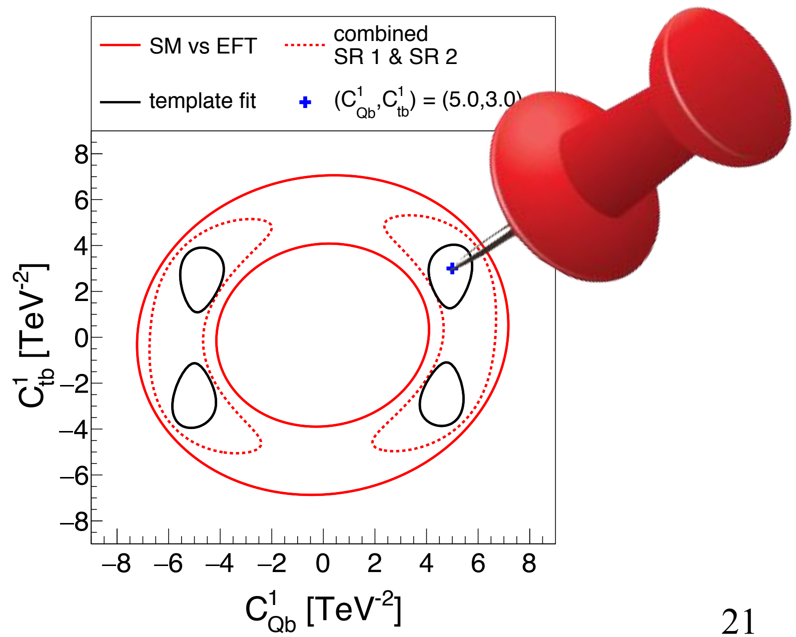
$t\bar{t}b\bar{b}$ is an indispensable component in a global fit of the top-quark interactions in the SMEFT at the LHC!

- 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

A. $t\bar{t}b\bar{b}$ is important background for $t\bar{t}H$ ($H \rightarrow b\bar{b}$).
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!

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

↓

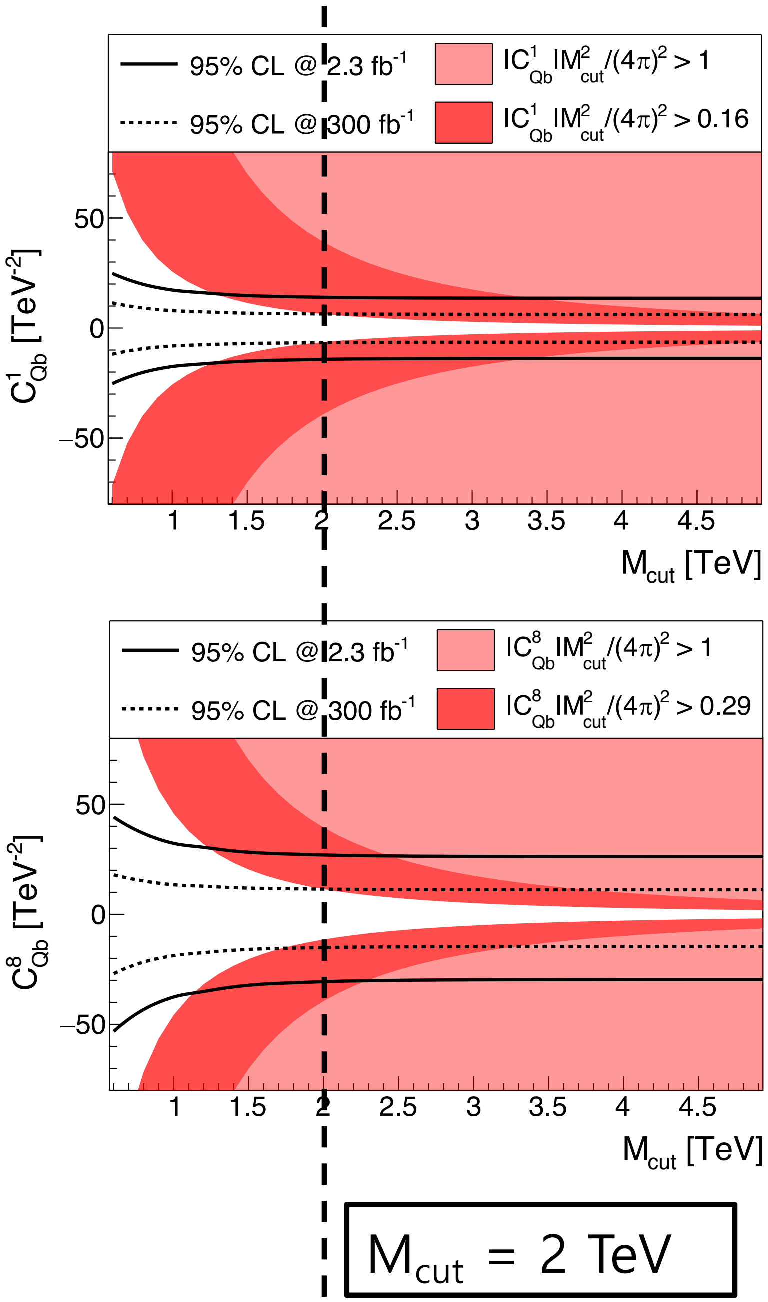
Parton showering
Pythia 8

↓

Detector simulation and event reconstruction
Delphes

Phase space after event reconstruction and selection

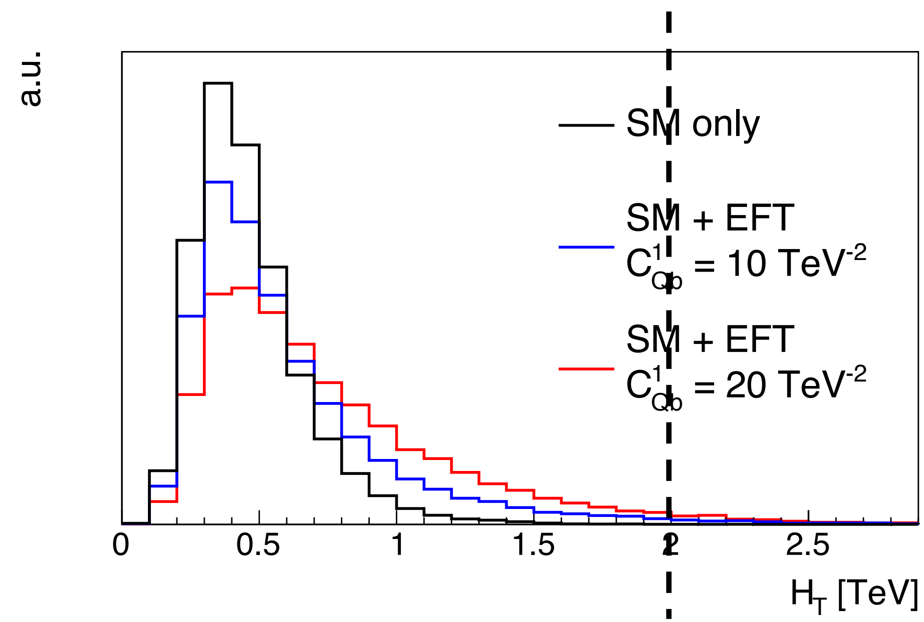
EFT validity



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

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

x-sec

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*

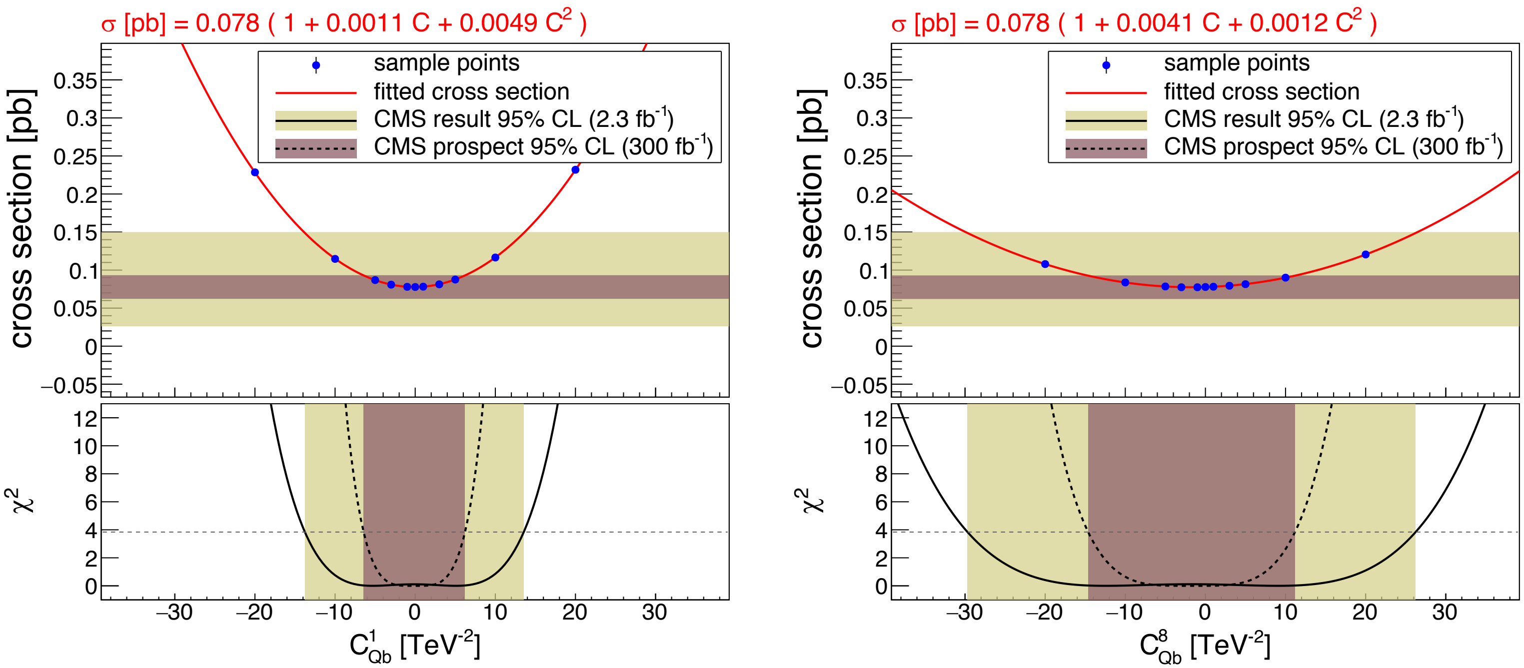
Integrated luminosity = 2.3 fb^{-1}

Visible phase space definition:

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

Projections for 300 fb-1: scaled stat. unc. and fixed syst. unc. of 10%

measured xsec = prediction of MadGraph



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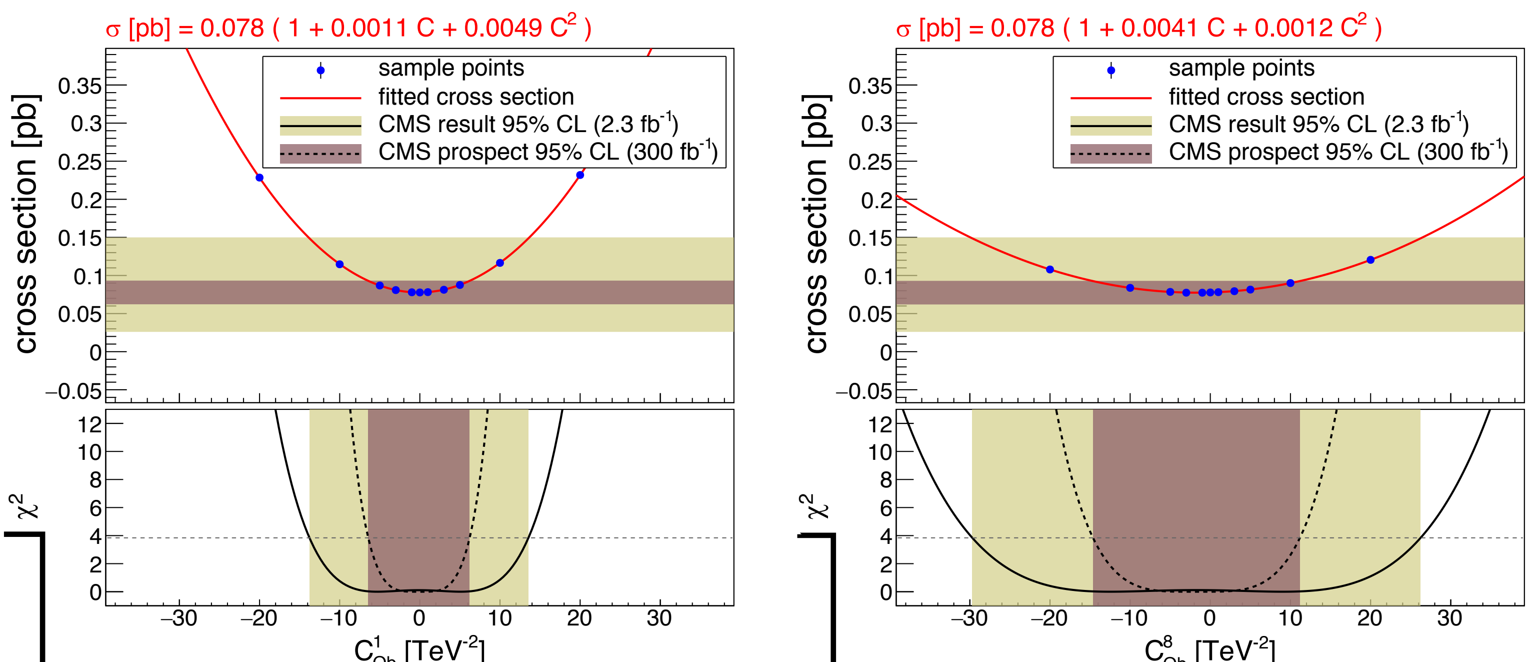
$$\sigma_{fit} = \sigma_{SM}\left(1 + p_1 \cdot C_i + p_2 \cdot C_i^2\right)$$

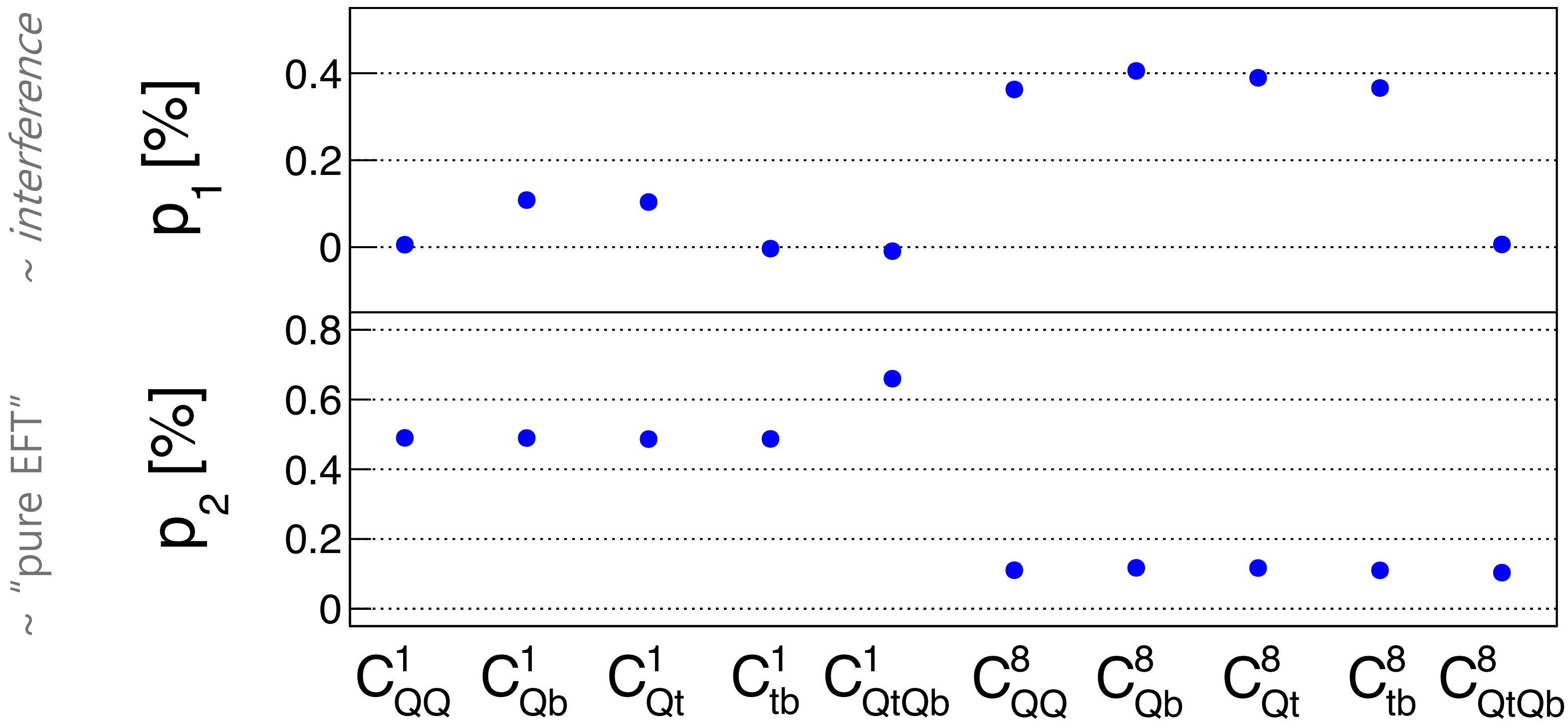


95% CL

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

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

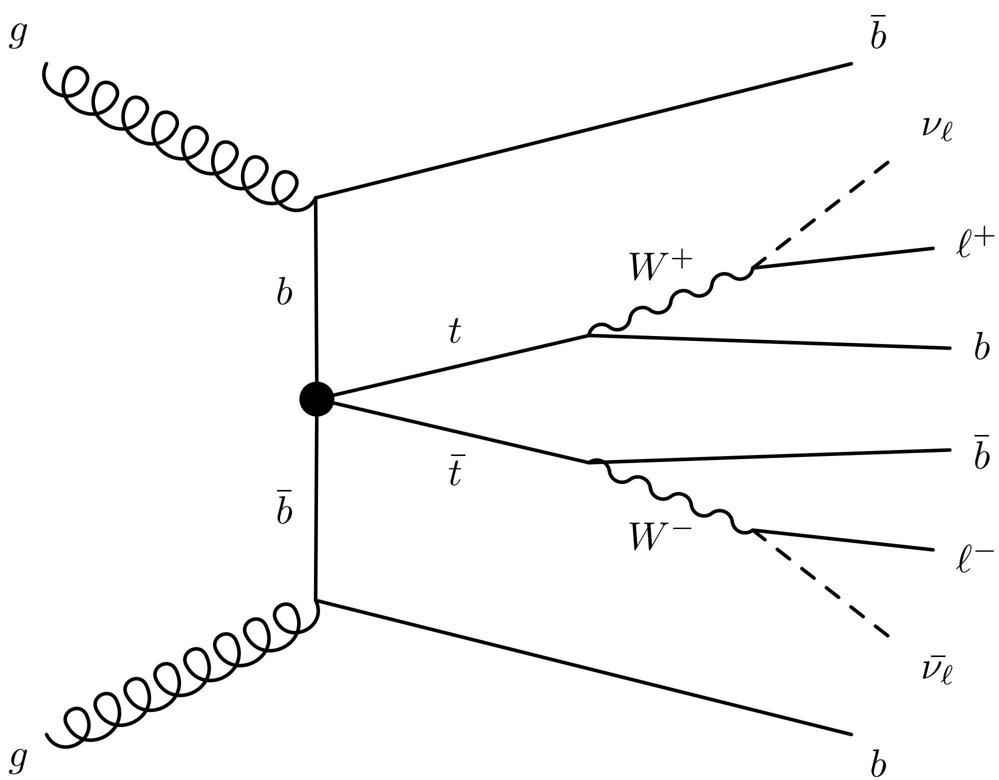
Color octet operators have larger interference (SM ~ gluon induced) but suppressed squared order contributions (color factor 2/9)

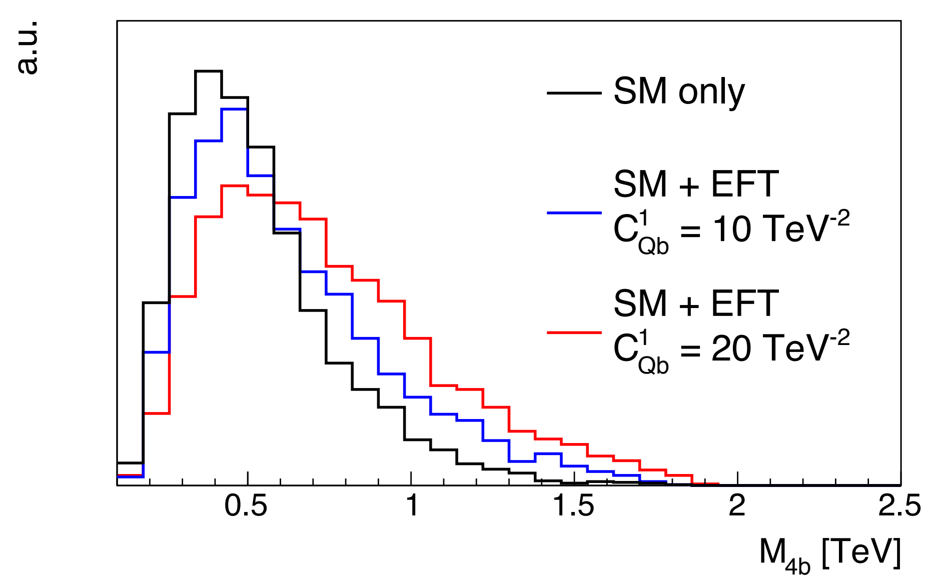
Tailoring the kinematical phase space

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) → $\mathbf{M_{4b}}$

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





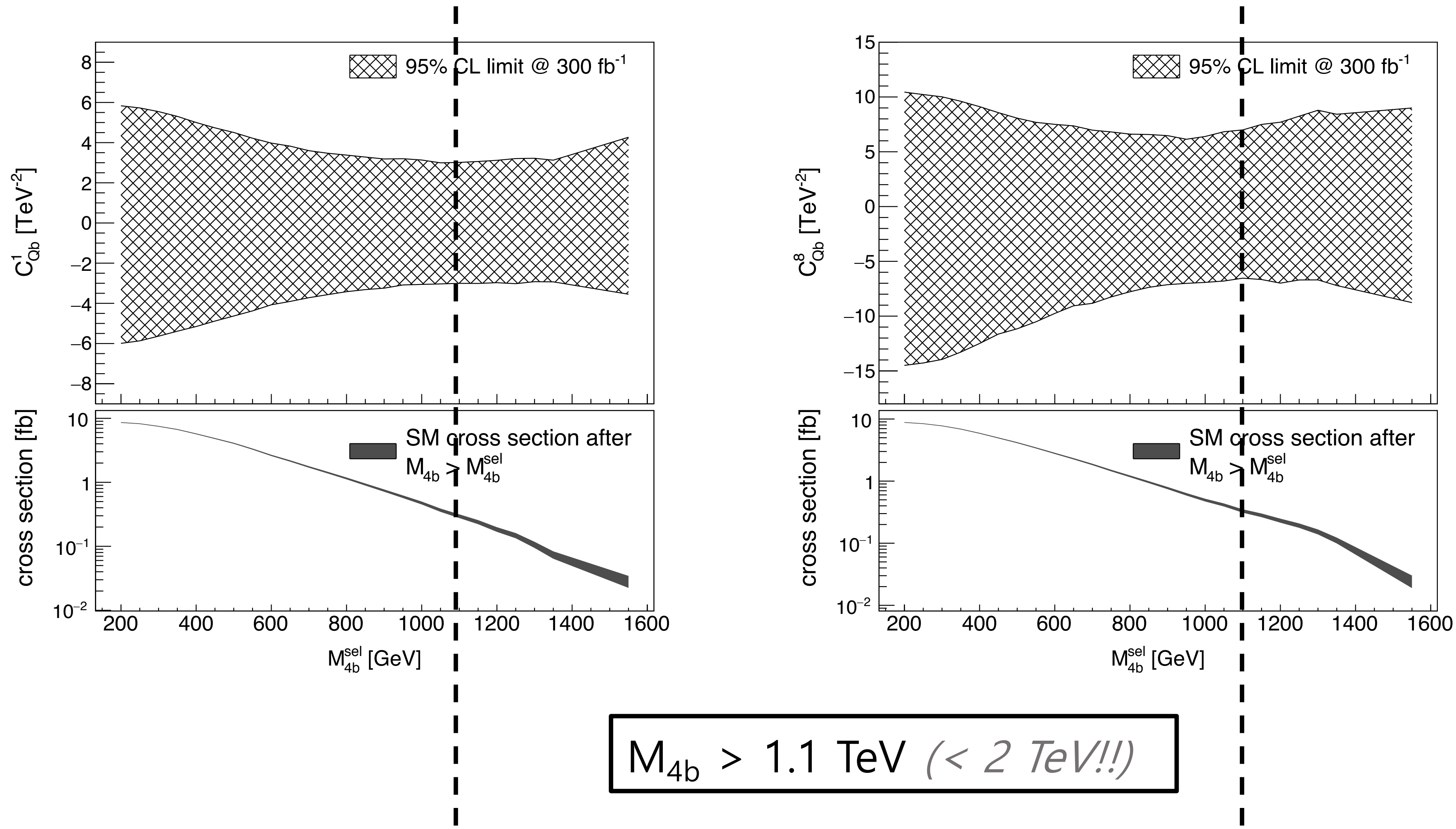
Tailoring the kinematical phase space

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

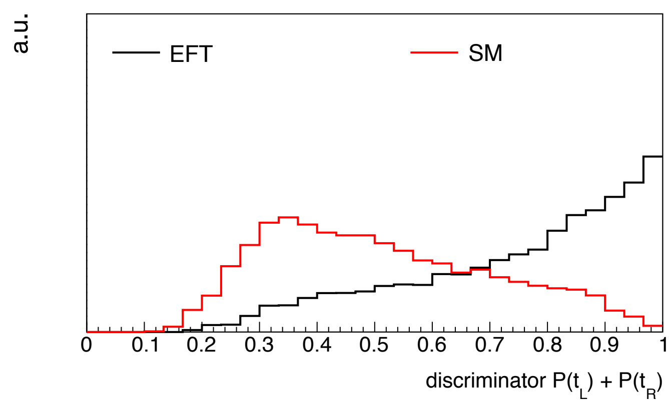


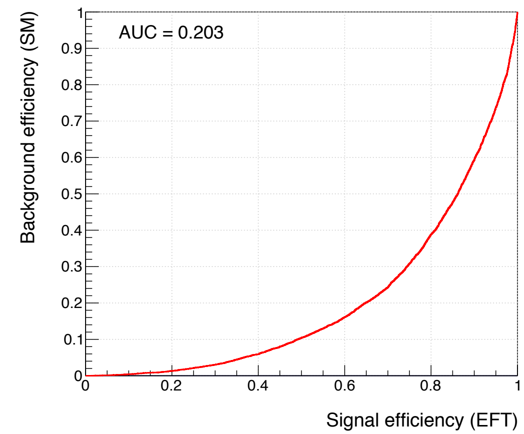
M_{4b} > 1.1 TeV *(< 2 TeV!!)*

Learning the effective operators

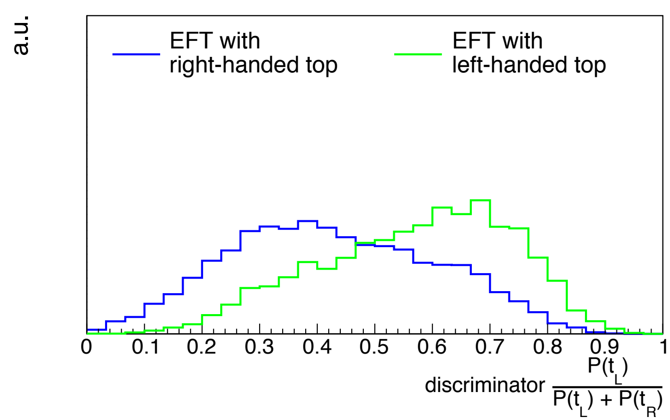
multiple operators

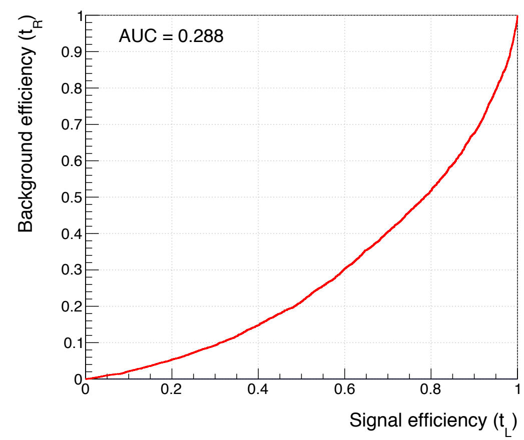
SM vs EFT





t_L vs t_R

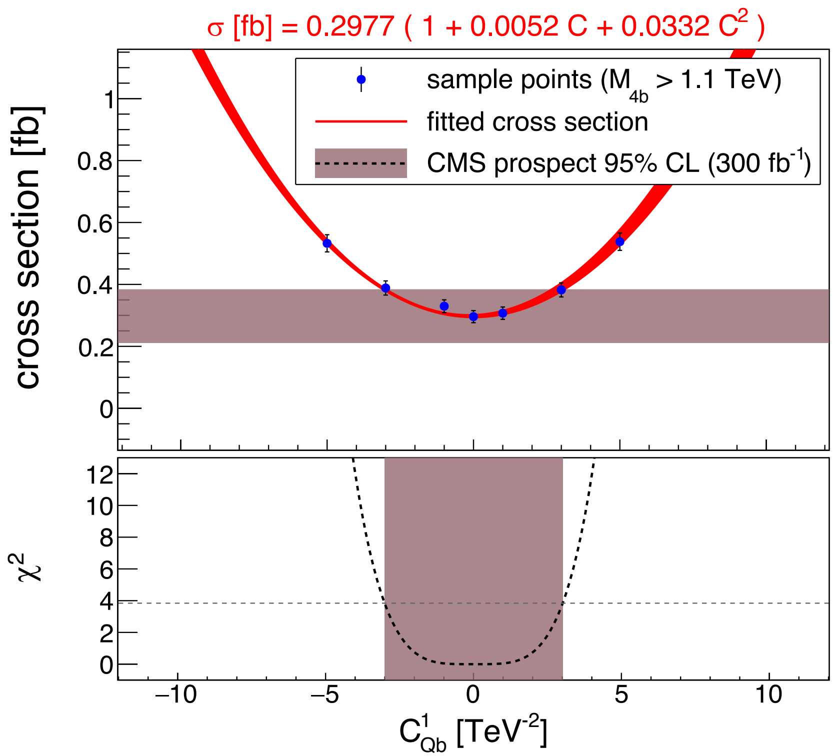


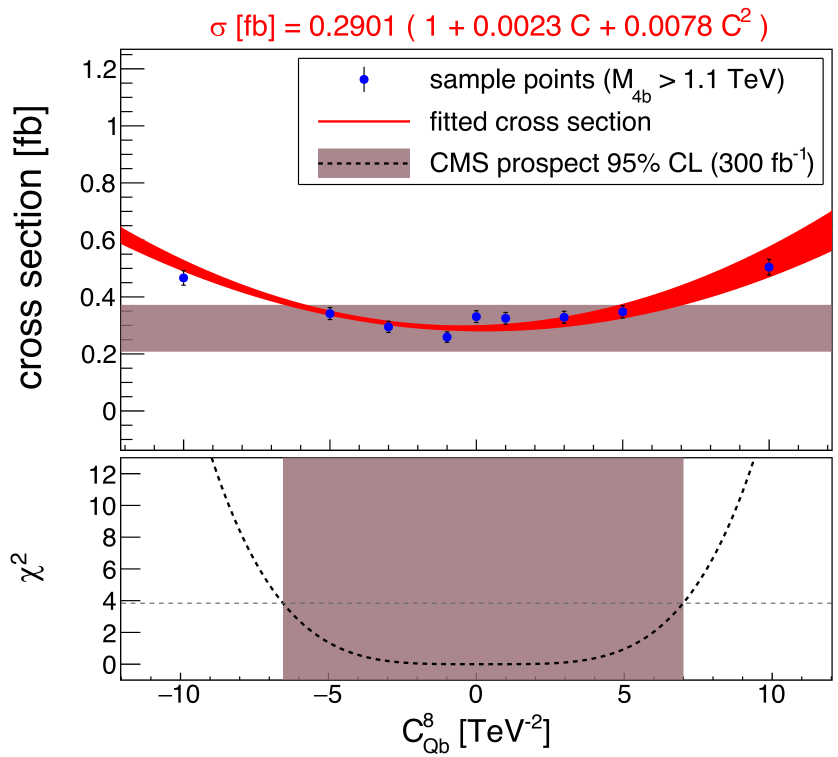


The NN has indeed learned to distinguish amongst t_L and t_R operators!

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}

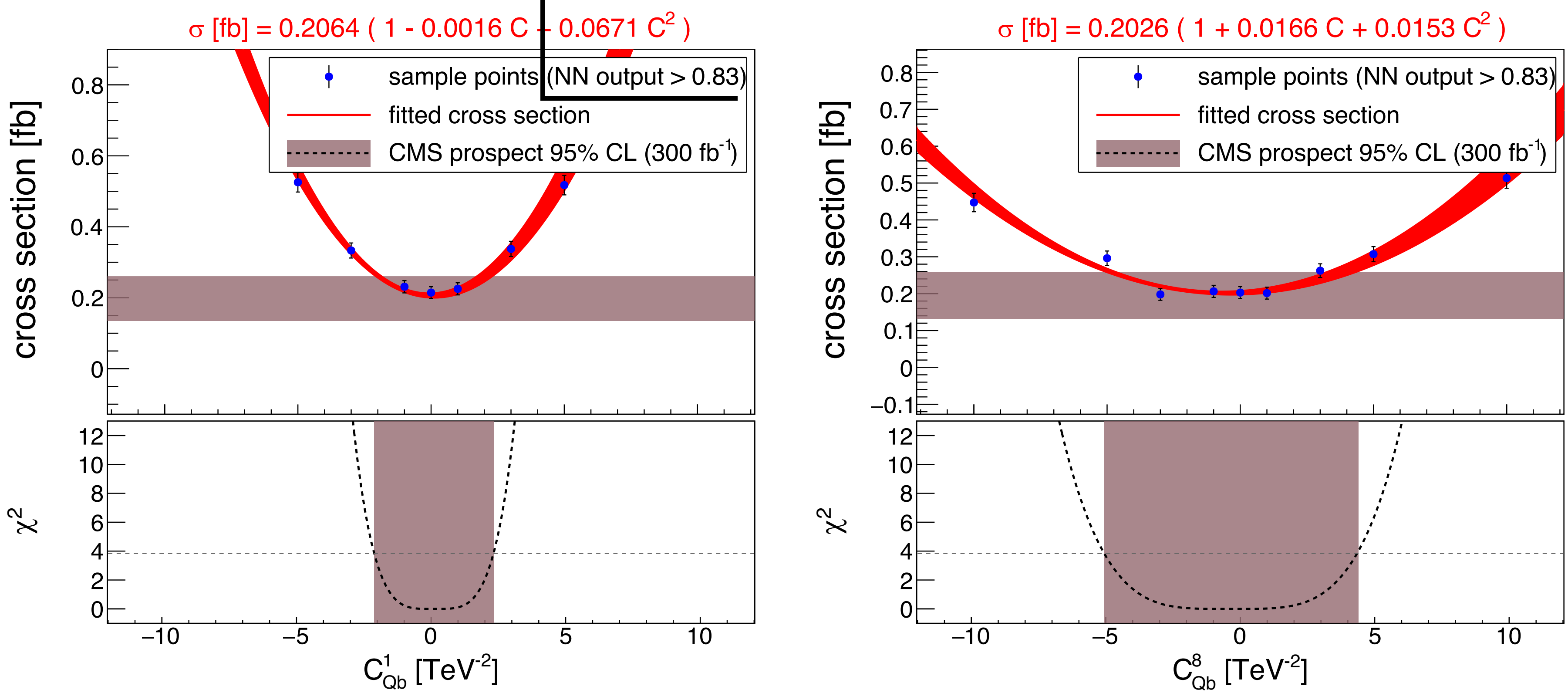
$C^8_{Qb} \in [-6.5, +7]$ TeV^{-2}
xsec: $C^8_{Qb} \in [-15, +10]$ TeV^{-2}

→ 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}

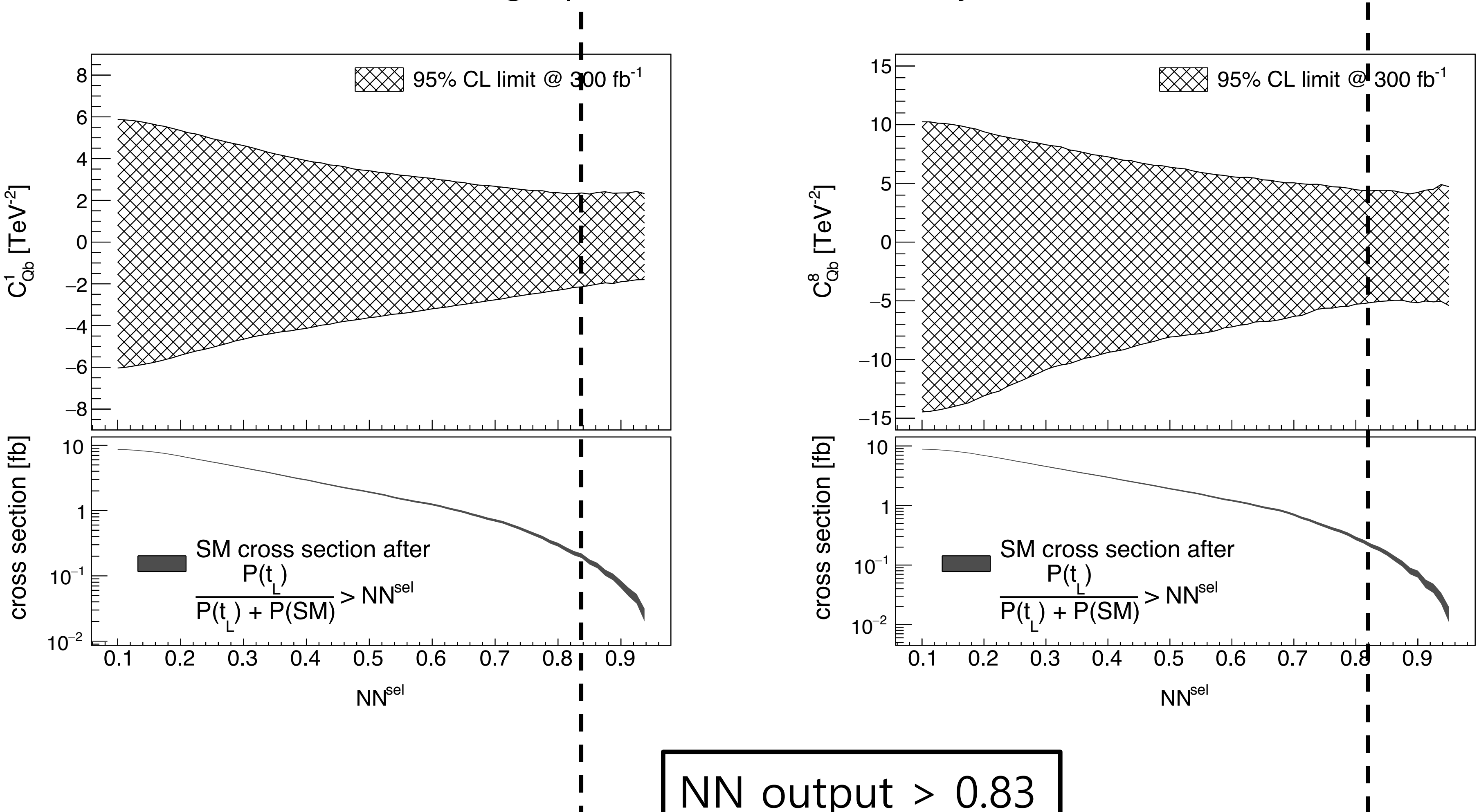
$C^8_{Qb} \in [-5, +4.3]$ TeV^{-2}
M_{4b} : $C^8_{Qb} \in [-6.5, +7]$ TeV^{-2}

→ significant further improvement!

Learning the effective operators
one operator at a time

NN

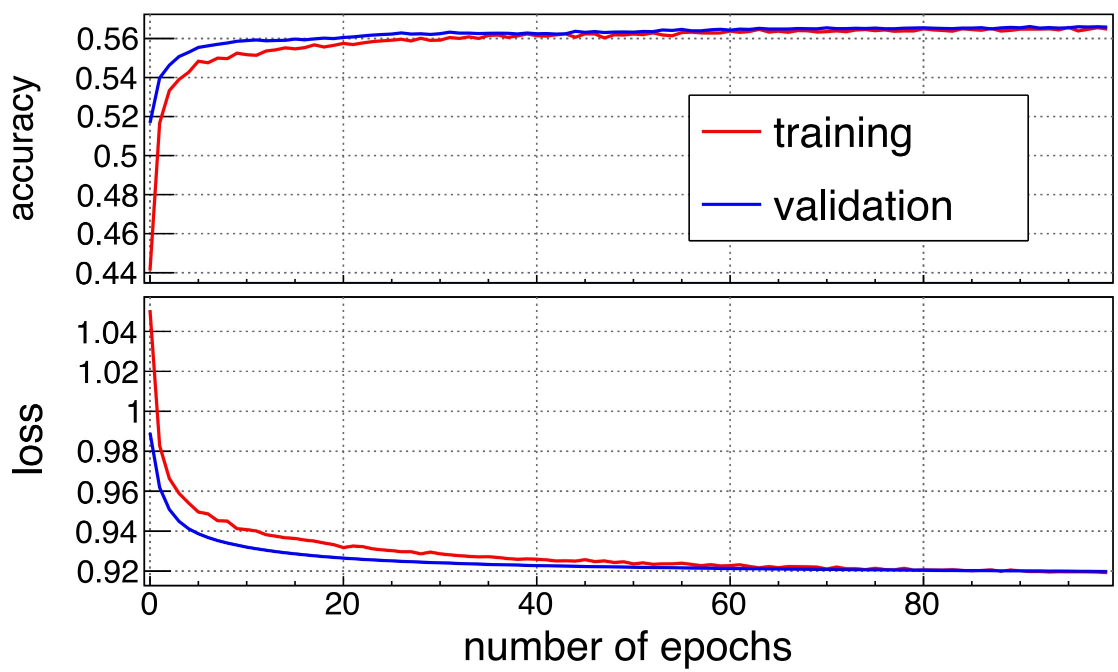
Question: What cut to choose on the NN ouput?
Answer: The one that optimizes the sensitivity!
→ increase relative population of EFT contributions
→ without blowing up statistical uncertainty on the SM measurement



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?

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}	$[-5.1, 4.1]$	$[-7.9, 6.6]$	$[-11, 8.7]$	$[-3.9, 3.8]$
	$\mu_{4t} < 1.87$	$\mu_{4t} < 5.22$		