Learning to pinpoint effective operators: a study of the ttbb signature

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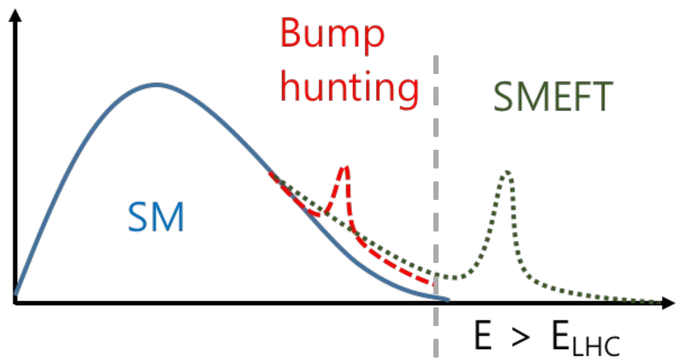


1. ttbb in SMEFT

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

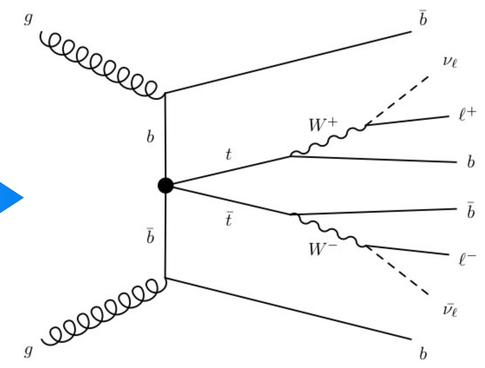
→ extend SM Lagrangian with dim. 6 operators(*).

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

The ttbb final state is sensitive to a set of 4-heavy-quark contact operators of dimension 6.

4-heavy-quark operators

Operator	$t\bar{t}b\bar{b}$	$t\bar{t}t\bar{t}$	
$O^1_{QQ} = \frac{1}{2}(\bar{Q}\,\gamma_\mu\,Q)(\bar{Q}\,\gamma^\mu\,Q)$,	✓	✓	$C^{(+)}_{QQ} = \frac{1}{2}C^1_{QQ} + \frac{1}{6}C^8_{QQ}$
$O^8_{QQ} = \frac{1}{2}(\bar{Q}\,\gamma_\mu\,T^A\,Q)(\bar{Q}\,\gamma^\mu\,T^A\,Q)$,	✓	✓	
$O^1_{tb} = (\bar{t}\,\gamma_\mu\,t)(\bar{b}\,\gamma_\mu\,b)$,	✓		
$O^8_{tb} = (\bar{t}\,\gamma_\mu T^A\,t)(\bar{b}\,\gamma_\mu\,T^A\,b)$,	✓		
$O^1_{tt} = (\bar{t}\,\gamma_\mu\,t)(\bar{t}\,\gamma_\mu\,t)$,		✓	
$O^1_{bb} = (\bar{b}\,\gamma_\mu\,b)(\bar{b}\,\gamma_\mu\,b)$,			
$O^1_{Qt} = (\bar{Q}\,\gamma_\mu\,Q)(\bar{t}\,\gamma^\mu\,t)$,	✓	✓	
$O^8_{Qt} = (\bar{Q}\,\gamma_\mu\,T^A\,Q)(\bar{t}\,\gamma^\mu\,T^A\,t)$,	✓	✓	
$O^1_{Qb} = (\bar{Q}\,\gamma_\mu\,Q)(\bar{b}\,\gamma^\mu\,b)$,	✓		
$O^8_{Qb} = (\bar{Q}\,\gamma_\mu\,T^A\,Q)(\bar{b}\,\gamma^\mu\,T^A\,b)$,	✓		
$O^1_{QtQb} = (\bar{Q}\,t)\,\varepsilon\,(\bar{Q}\,b)$,	✓		
$O^8_{QtQb} = (\bar{Q}\,T^A\,t)\,\varepsilon\,(\bar{Q}\,T^A\,b)$.	✓		



(*) leading L and B conserving contributions

2. The virtues of ttbb

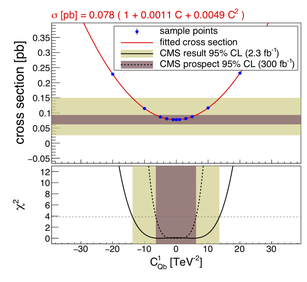
- Sufficiently large cross section (~ 3 pb) to exploit differential information.
- Able to constrain directly a set of (previously unconstrained) 4-heavy-quark operators.
- Lifts degeneracy in direction of parameter space (present in four top final state).

→ Indispensable component in a global fit of top quark interaction in the SMEFT.

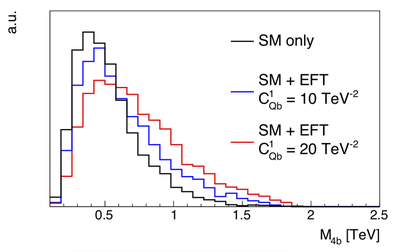
3. Sensitivity study

Inclusive cross section → **Invariant mass of four b jets (M_{4b})** → **Machine learning (Neural Network)**

Recent CMS measurement:
Phys. Lett. B 776 (2018) 355
$\sigma_{t\bar{t}b\bar{b},CMS} = 88 \pm 12(stat.) \pm 29(syst.)$ fb
This measurement can be translated into limits on the Wilson coefficients.



Select EFT-enriched phase space by applying a selection on the invariant mass of the 4 b jets.
→ *need to move to reconstructed phase space.*



Combine all kinematical information in a neural network (NN).
→ *more effective selection of the EFT enriched phase space.*

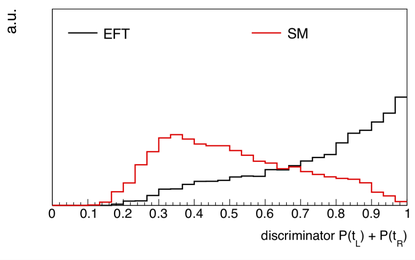
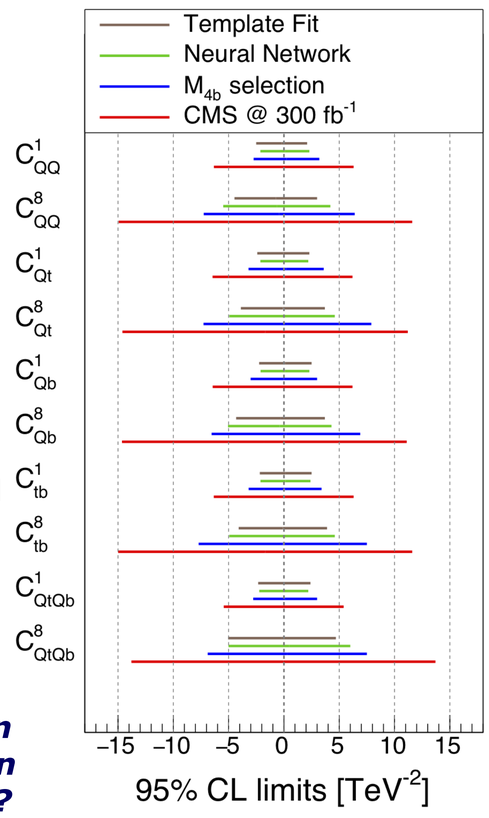


Figure: Summary of the 95% CL intervals on the Wilson coefficients, allowing only one of them to be non-zero at a time.

A clear improvement in the limits is observed moving from x-sec → M_{4b} → NN.

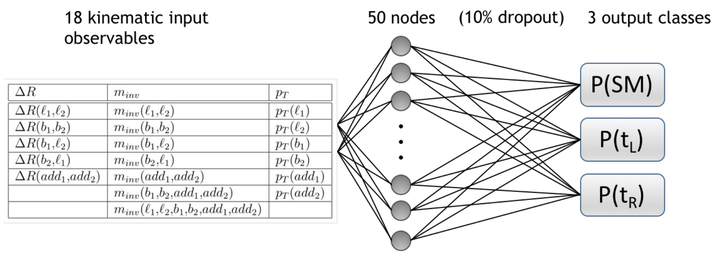
Disclaimer: These intervals are sensitivity limits (assuming only one non-zero coefficient at any time) and are in general optimistic. The relative improvement however shows the strength of selecting an EFT-dominated region of phase space.

Q: What can we do when multiple non-zero Wilson coefficients are allowed?



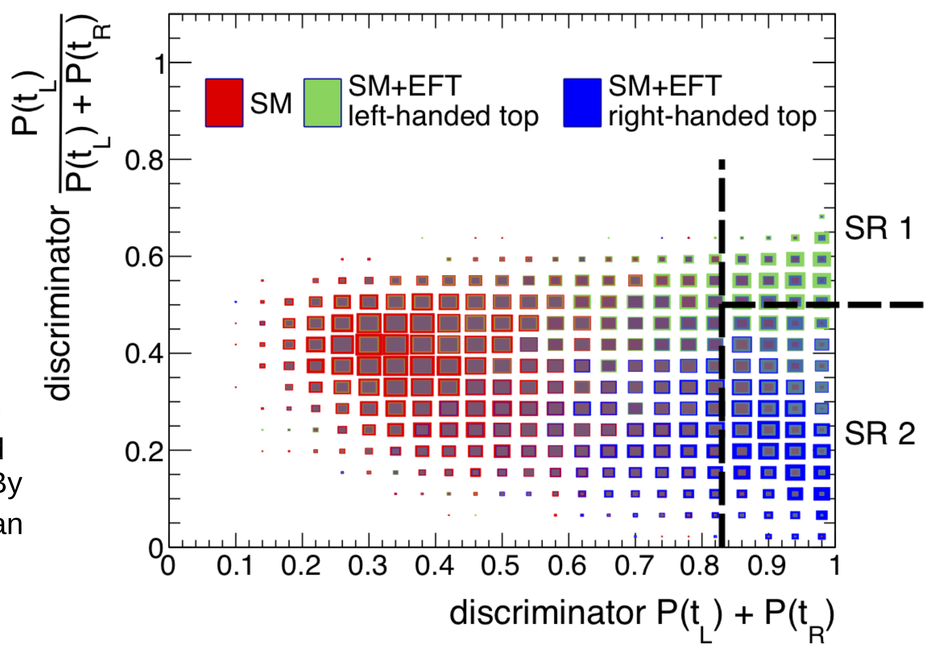
4. Learning the effective operators

Case study: can a NN learn to distinguish between operators with left-handed top-quark currents (t_L) and right-handed top-quark currents (t_R)? If so, can we use this to improve limits on the Wilson coefficients?
A shallow neural network was constructed that combines 18 kinematical variables to predict one of ***three output classes***. From the network outputs, two discriminators are built; one to distinguish between SM and EFT in general, and another one to distinguish t_L from t_R.

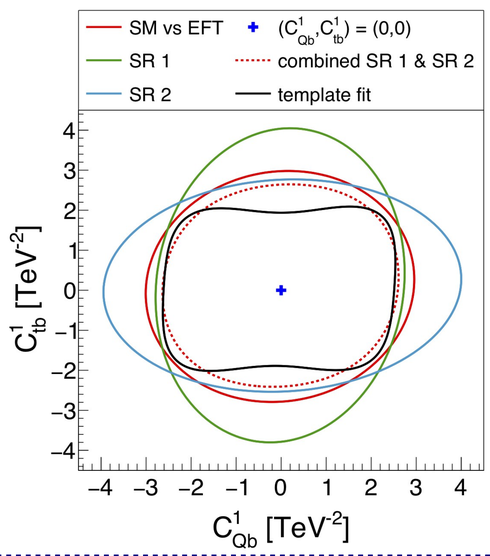


ΔR	m_{inv}	p_T
$\Delta R(\ell_1,\ell_2)$	$m_{inv}(\ell_1,\ell_2)$	$p_T(\ell_1)$
$\Delta R(b_1,b_2)$	$m_{inv}(b_1,b_2)$	$p_T(\ell_2)$
$\Delta R(b_1,\ell_2)$	$m_{inv}(b_1,\ell_2)$	$p_T(b_1)$
$\Delta R(b_2,\ell_1)$	$m_{inv}(b_2,\ell_1)$	$p_T(b_2)$
$\Delta R(add_1,add_2)$	$m_{inv}(add_1,add_2)$	$p_T(add_1)$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

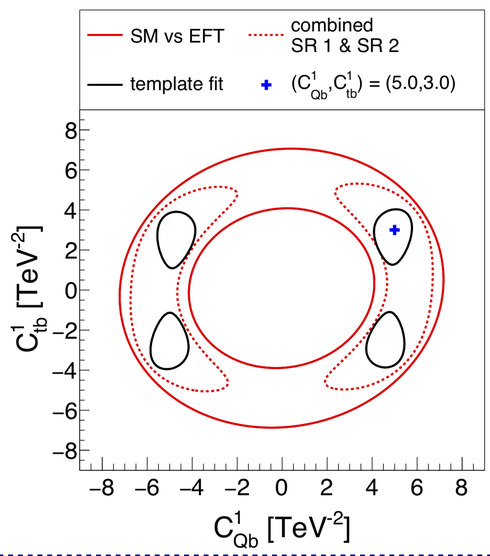
Figure (right): the x-axis represents the SM vs EFT discriminator, whereas the y-axis represents the t_L vs t_R discriminator. SM contributions are located to the left, whereas the EFT contributions are located to the upper right (t_L) and lower right (t_R) corners. By combining limits in dedicated signal regions, we can improve the limits/confidence intervals!



Scenario 1: observation of the SM



Scenario 2: observation of an EFT signal



→ template fits to the 2D NN outputs give most stringent limits / confidence intervals!

5. Conclusion and outlook

- *ttbb is a valuable asset to a global fit of the top quark interactions in the SMEFT framework.*
- *Multi-class NNs allow to identify contributions from specific operators, leading to an improved sensitivity.*

Outlook:
- Include interference effects in the training
- More advanced (deep) machine learning methods
- Perform a full global fit including all operators
- Question: can the NN identify each individual operator or are there limitations?

ArXiv: 1807.02130, Submitted to JHEP