Four-top final states as a probe of Two-Higgs-Doublet models

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DESY.

Motivation

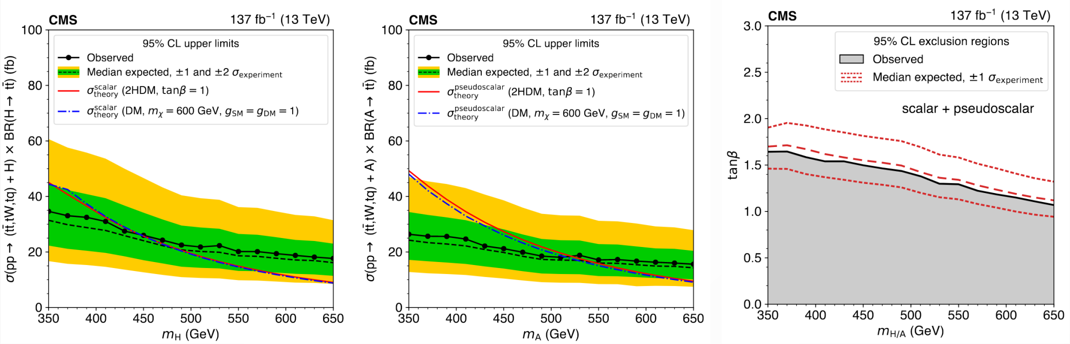
- The $t\bar{t}t\bar{t}$ cross-section can be used to constrain the Yukawa coupling of top quarks to Higgs bosons and can be enhanced by BSM contributions
- Four top production with $gg \to H \to t\bar{t}$ often have the largest branching ratios (large coupling)
- Existing BSM interpretations are limited to the alignment limit in selected models
- Implementation in the public code `HiggsBounds` which is now part of `HiggsTools`
- Study impact on Two-Higgs-Doublet models where four-top production places constraints on the low $\tan\beta$ region

Outline

- Four-top final-states at CMS
- Cross-section fit formulas
- Monte-Carlo- and detector-simulation setup
- Preliminary results
- Outlook

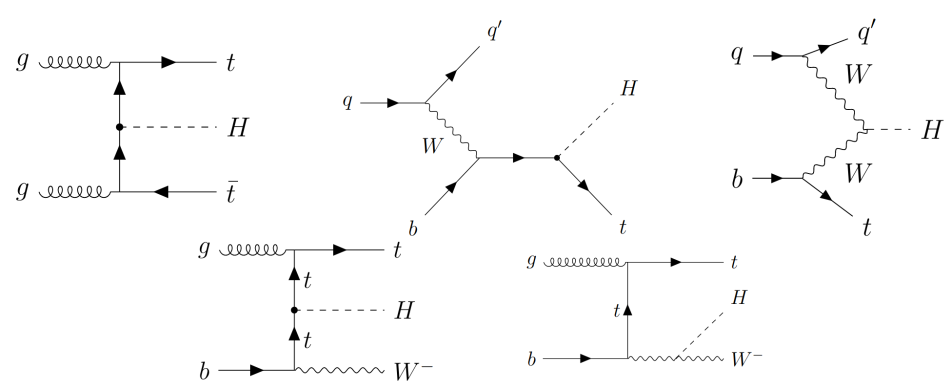
Four-top final-states at CMS *arxiv[1908.06463]*

- We want to obtain upper limits on $\sigma(pp \to (t\bar{t}, tW, t) + X) \times \text{BR}(X \to t\bar{t})$, using Monte-Carlo and detector simulations.

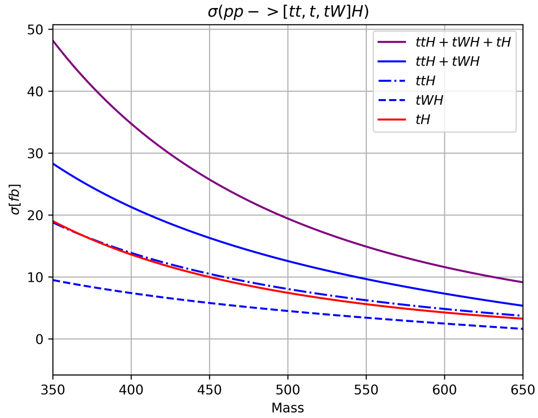


Four-top final-states at CMS

- We specifically look at the subchannels of $t\bar{t}H$, tH and tWH production.



Cross-section of sub-channels



- ttH and tWH can not be measured independently, so tWH should be included
- The cross-section of tH is of similar size as ttH and should not be neglected

Effective model description

- Effective Lagrangian similar to Higgs-characterization model: *arxiv:[1306.6464]*

$$\mathcal{L}_{eff} = \mathcal{L}_{Yuk} + \mathcal{L}_{V} \tag{1}$$

$$\mathcal{L}_{Yuk} = -\frac{y_t^{SM}}{\sqrt{2}}\bar{t}(c_t + i\gamma_5\tilde{c}_t)tX \tag{2}$$

$$\mathcal{L}_{V} = c_V X\left(\frac{M_Z^2}{\nu}Z_\mu Z^\mu + 2\frac{M_W^2}{\nu}W_\mu^+ W^{-\mu}\right) \tag{3}$$

- y_t^{SM} is the SM top-Yuakwa coupling, X denotes a generic Scalar and t,W,Z denote the top-quark and Vector-boson fields
- $c_t, \tilde{c}_t, c_V$ are the $\mathcal{CP}$-even and $\mathcal{CP}$-odd coupling to top-quarks and Vector-bosons (rescaled to the SM)

Cross-section fit formulas

Derive fit formulas for the total cross-section and in each signal region for the subchannels $tH, t\bar{t}H, tWH, ggH$:

$$\sigma \propto (a_1 c_V^2 + a_2 c_V c_t + a_3 c_t^2 + a_4 \tilde{c}_t^2) \cdot (b_1 c_t^2 + b_2 \tilde{c}_t^2) \tag{4}$$

Where the first bracket comes from the production and the second from the decay. We get:

$$\sigma \propto c_1 c_v^2 c_t^2 + c_2 c_V^2 \tilde{c}_t^2 + c_3 c_V c_t^3 + c_4 c_V c_t \tilde{c}_t^2 + c_5 c_t^4 + c_6 c_t^2 \tilde{c}_t^2 + c_7 \tilde{c}_t^4 \tag{5}$$

All other possible terms are zero because of the non-interference of CP-even and CP-odd contributions

Cross-section fit formulas

The coefficients c_{1-7} can be extracted by calculation cross-sections for 7 different parameter points.

- $c_t = 1, \tilde{c}_t = 0, c_V = 0 \longrightarrow \sigma_1 = c_5$
- $c_t = 0, \tilde{c}_t = 1, c_V = 0 \longrightarrow \sigma_2 = c_7$
- $c_t = 1, \tilde{c}_t = 1, c_V = 0 \longrightarrow \sigma_3 = c_5 + c_6 + c_7$
- $c_t = 1, \tilde{c}_t = 0, c_V = 1 \longrightarrow \sigma_4 = c_1 + c_3 + c_5$
- $c_t = 1, \tilde{c}_t = 0, c_V = 2 \longrightarrow \sigma_5 = 4c_1 + 2c_3 + c_5$
- $c_t = 1, \tilde{c}_t = 1, c_V = 1 \longrightarrow \sigma_6 = c_1 + c_2 + c_3 + c_4 + c_5 + c_6 + c_7$
- $c_t = 1, \tilde{c}_t = 1, c_V = 2 \longrightarrow \sigma_7 = 4c_1 + 4c_2 + 2c_3 + 2c_4 + c_5 + c_6 + c_7$

Monte-Carlo- and detector-simulation setup

- Use `MadGraph5` to calculate the total cross-section σ_{tot} for each subchannel with 7 different coupling-configurations
- We us `NNPDF3.0` for the Parton Distribution Functions
- We generate each configuration for masses of a generic scalar X between 350 and 1000 GeV by using the Higgs-characterization model with 50000-100000 events for each.
- The scalars can have couplings top quarks $(c_t, \tilde{c}_t)$ and vector bosons (c_V)
- As a result the scalar can be either CP-even, CP-odd or CP-mixed, thus extending the original analysis

Monte-Carlo- and detector-simulation setup

- Using MadAnalysis we recast MadGraph5 results with an implementation of the analysis by *Fuks et al.* and application in *Maltoni et al.[arxiv:2104.09512]*
- We obtain the efficiency, which is the number of signal-events divided by the number of initial events:

$$\epsilon = \frac{N}{N_{\text{tot}}} \tag{6}$$

- The cross-section in each signal-region is then given by:

$$\sigma = \epsilon \cdot \sigma_{\text{tot}} \tag{7}$$

- The Limit on $\sigma \times BR$ is obtained from the number of signal events. E.g, in the CP-even case, we have

$$N_{\text{signal}} = c_t^4 \mathcal{L} \cdot \left[\sigma(t\bar{t}H, H \to t\bar{t})\epsilon_{t\bar{t}H} + \sigma(tH, H \to t\bar{t})\epsilon_{tH} + \sigma(tWH, H \to t\bar{t})\epsilon_{tWH}\right]_{c_t=1} \tag{8}$$

Monte-Carlo- and detector-simulation setup

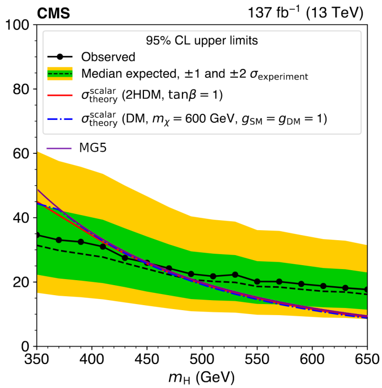
- We combine the 14 signal regions into one region.

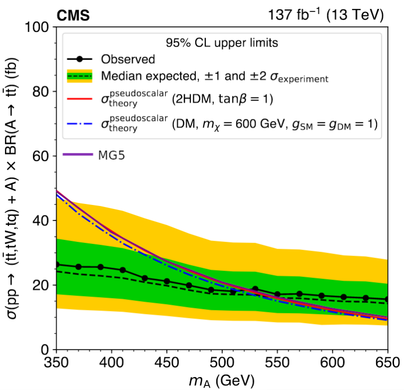
N_ℓ	N_b	N_j	Region	$t\bar{t}t\bar{t}$ (SM - CMS)
2	2	6	SR1	1.89 ± 1.14
2	2	7	SR2	1.04 ± 0.57
2	2	$\geq$8	SR3	0.67 ± 0.38
2	3	5	SR4	1.51 ± 0.85
2	3	6	SR5	1.61 ± 0.90
2	3	7	SR6	1.14 ± 0.66
2	3	$\geq$8	SR7	0.85 ± 0.47
2	≥ 4	$\geq$5	SR8	2.08 ± 1.23

N_ℓ	N_b	N_j	Region	$t\bar{t}t\bar{t}$ (SM - CMS)
≥ 3	2	5	SR9	0.66 ± 0.38
≥ 3	2	6	SR10	0.33 ± 0.21
≥ 3	2	$\geq$7	SR11	0.22 ± 0.13
≥ 3	≥ 3	4	SR12	0.56 ± 0.32
≥ 3	≥ 3	5	SR13	0.66 ± 0.38
≥ 3	≥ 3	$\geq$6	SR14	0.76 ± 0.45

Figure: *[arxiv:2104.09512]*

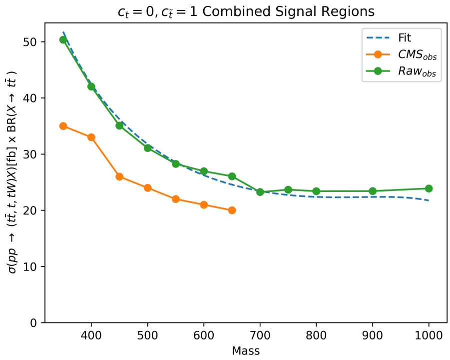
Preliminary results

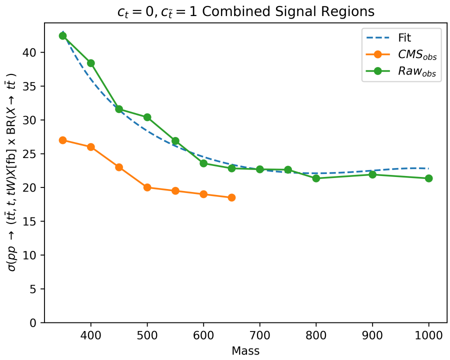




- Good agreement of the theory predicted cross-section.

Preliminary results





- Slightly weaker limit but overall good agreement
- We sum up the SR of the cut-based analysis
- CMS limit uses BDT analysis and can combine signal regions more carefully

Summary

Work done

- We generated and recasted Monte-Carlo events for four-top final states with a generic scalar X
- Derivation of Fit formulas for the total cross-section and in each signal region
- Upper-limits on the cross-section times branching fraction in the alignment limit

Outlook

- Upper-limits on the cross-section times branching fraction for CP-odd and CP-mixed states
- Implementation in the public code `HiggsBounds`
- Detailed study on the impact in Two-Higgs-Doublet models and other BSM models by four-top final states