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

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Motivation

- Constrain Multi-Higgs models using CMS measurements of four top production in pp-collisions
- Original BSM interpretation is limited to the 2HDM alignment limit and no CP-mixed states
- Using Monte-Carlo and detector simulations, we want to obtain upper limits on $\sigma(pp \to (t\bar{t}, tW, t) + X) \times \mathrm{BR}(X \to t\bar{t})$ and $\tan\beta$.
- Impact on the low $\tan\beta$ region in Two-Higgs-Doublet models
- Implementation in the public code `HiggsBounds` which is now part of `HiggsTools`

Outline

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

What is HiggsTools?

HiggsTools is an overhaul of HiggsBounds-5 and HiggsSignals-2 containing three parts:

HiggsPredictions

- handles user input for model predictions
- tabulated cross sections and BRs(SM, effC,...)
- common process definitions and clustering

HiggsBounds

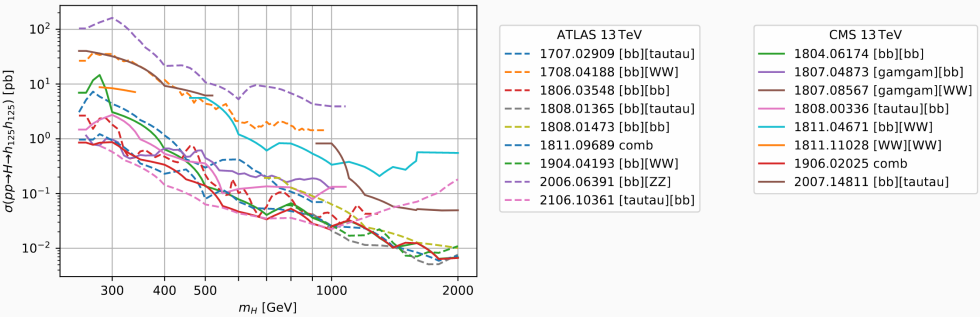
- compares experimental search results to provided model predictions

HiggsSignals

- compares experimental measurements to provided model predictions

There are currently over 200 analysis implemented!

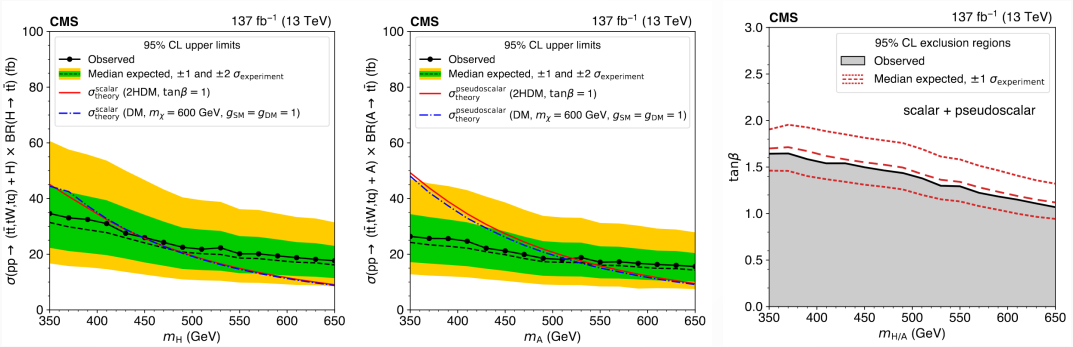
Example - Res. SM-Higgs pair production



- Limits automatically checked by HiggsBounds for resonant SM-Higgs pair production

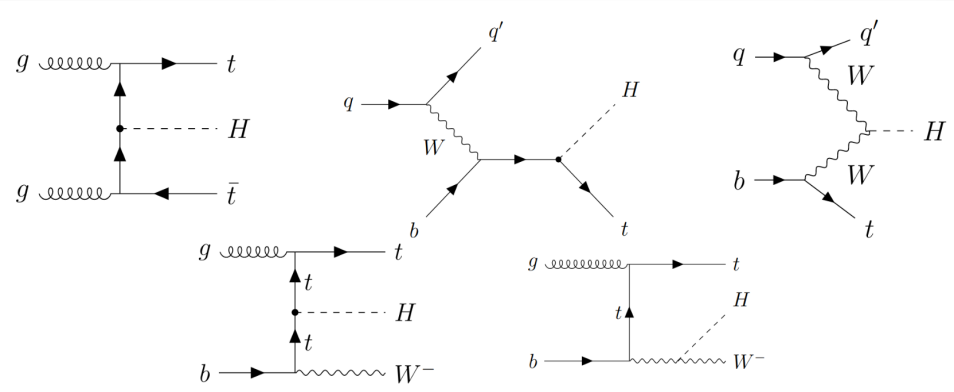
Four-top final-states at CMS *arxiv[1908.06463]*

- We analyze the impact of four-top final states from pp-collisions at CMS with an integrated luminosity of 137fb^{-1}.



Four-top final-states at CMS

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



Effective model description

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

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

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

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

- 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 $tH, t\bar{t}H, tWH$:

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

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

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

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

Monte-Carlo- and detector-simulation setup

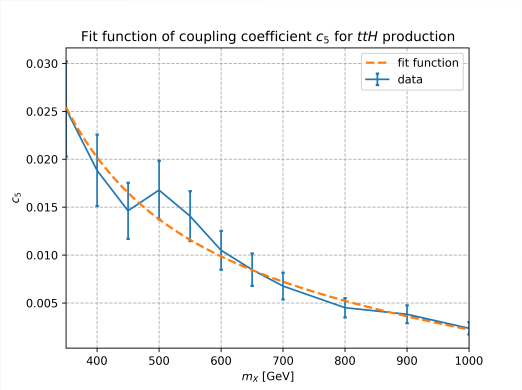
- `MadGraph5` to calculate the total cross-section σ_{tot} for each subchannel with 7 different coupling-configurations with `NNPDF3.0`
- Each configuration for masses between 350 and 1000 GeV with the Higgs-characterization model
- Using `MadAnalysis` we recast `MadGraph5` results with an implementation of the CMS analysis by *Fuks et al.* and application in *Maltoni et al.[arxiv:2104.09512]*
- We obtain the efficiency and cross-section in each signal-region:

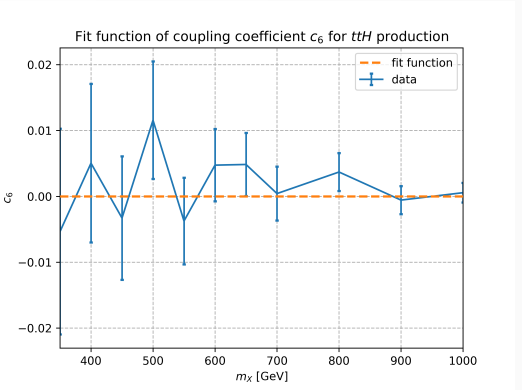
$$\epsilon = \frac{N}{N_{\text{tot}}}, \quad \sigma = \epsilon \cdot \sigma_{\text{tot}} \tag{6}$$

- The Limit on $\sigma \times BR$ is obtained with the relation:

$$N_{\text{signal}} = c_t^4 \mathcal{L} \cdot [\sigma(t\bar{t}H, H \to t\bar{t})\epsilon_{t\bar{t}H} + \sigma(tH, H \to t\bar{t})\epsilon_{tH} + \sigma(tWH, H \to t\bar{t})\epsilon_{tWH}]_{c_t=1} \tag{7}$$

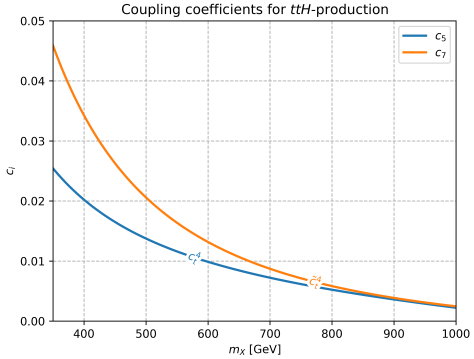
Cross-section coefficient fit functions

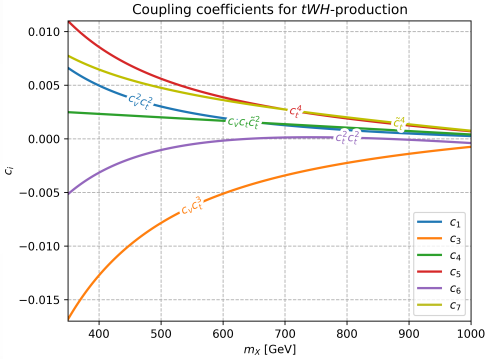




- Examplary fit functions of the cross-section coefficients comapred to the data

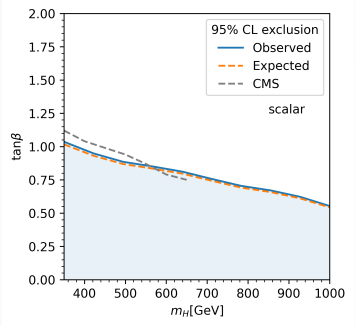
Cross-section coefficient fit functions

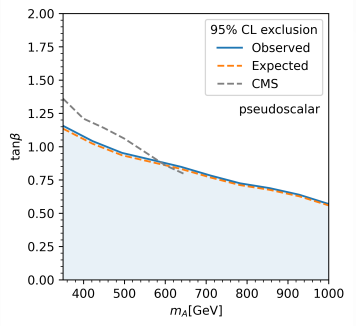


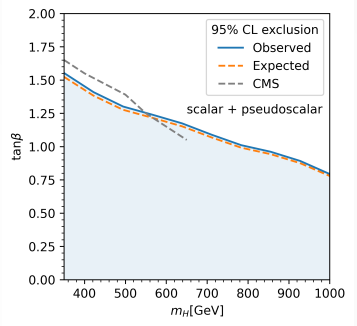


- Overview of all coefficients for the ttH- and tWH-channels.
- Shows large contribution of coefficients corresponding to vertices with c_V

tanβ-limits

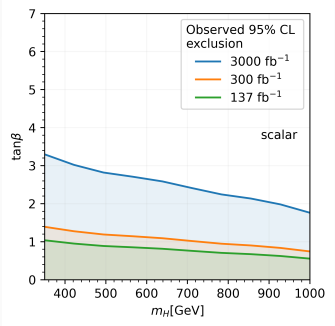


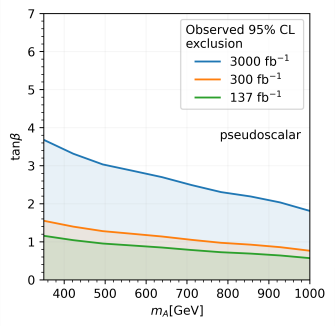


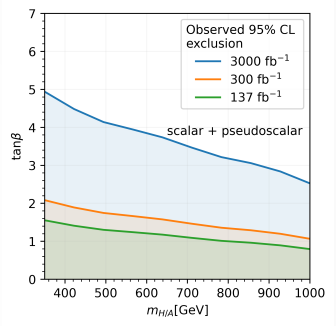


- Slightly weaker than CMS for low masses
- Extended mass range up to 1 TeV

Projection of tanβ-limits to High Lumi LHC (naive scaling)







- The current limit can already exclude tanβ up to 1.6 for a scalar plus pseudoscalar
- Scaling to High Lumi LHC could exclude low mass scenarios up to tan$\beta = 5$

Field expansion around vevs:

$$\Phi_1 = \begin{pmatrix} \chi_1^+ \\ \phi_1 \end{pmatrix} = \begin{pmatrix} \chi_1^+ \\ v_1 + \dfrac{\rho_1 + i\eta_1}{\sqrt{2}} \end{pmatrix} \Phi_2 = \begin{pmatrix} \chi_2^+ \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \chi_2^+ \\ v_2 + \dfrac{\rho_2 + i\eta_2}{\sqrt{2}} \end{pmatrix}$$

$$S = v_S + \frac{\rho_S}{\sqrt{2}} \tag{8}$$

Symmetries:

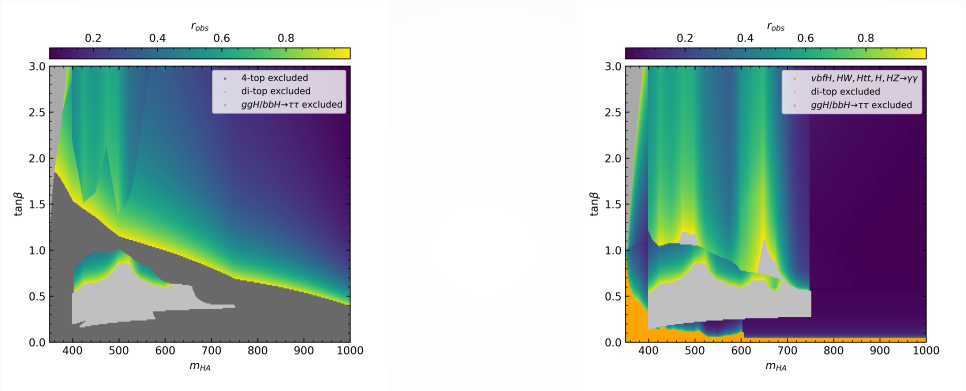
$$\mathbb{Z}_2 \ : \ \Phi_1 \to \Phi_1, \qquad \Phi_2 \to -\Phi_2, \qquad S \to S \tag{9}$$

$$\mathbb{Z}_2' \ : \ \Phi_1 \to \Phi_1, \qquad \Phi_2 \to \Phi_2, \qquad S \to -S \tag{10}$$

Free parameters:

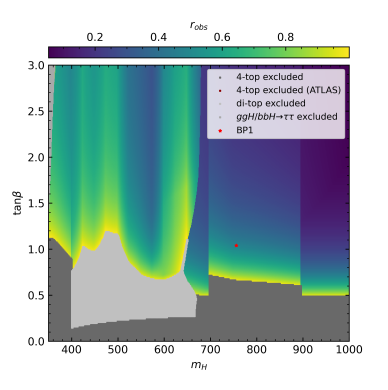
$$\tan\beta, \quad \alpha_{1,2,3}, \quad m_{h_1}, \quad m_{h_2}, \quad m_{h_3}, \quad m_{a_1}, \quad m_{12}^2, \quad m_{H^\pm}, \quad v_S \tag{11}$$

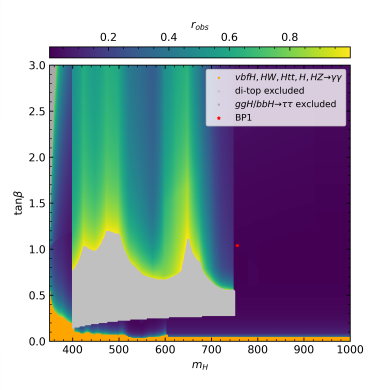
Impact on the $m_{H/A}$-tanβ plane in the N2HDM



- Di-top analysis can be stronger than four-top in the 400-700 GeV range
- The four-top analysis expands the excluded parameter region, especially for low masses and tanβ

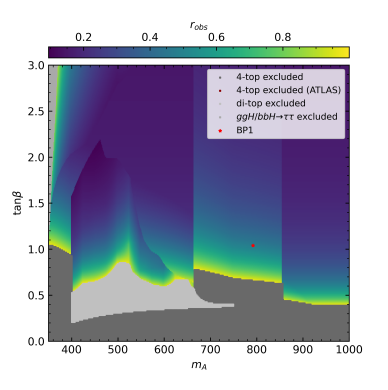
Impact on the m_H-tanβ plane in the N2HDM

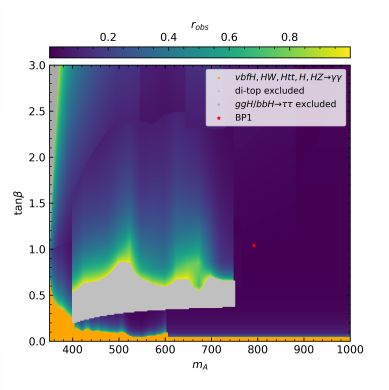




- Very similar to the mass degenerate case, but overall weaker limit on tanβ
- "Bump" around 700-900 GeV comes from clustering in `Higgsbounds`

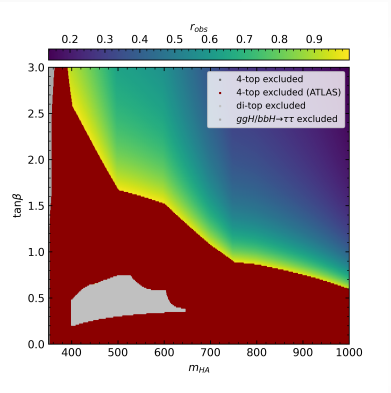
Impact on the m_A-tanβ plane in the N2HDM

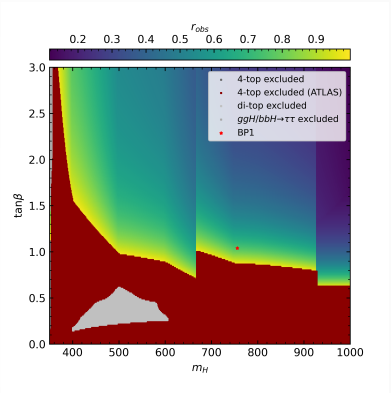




- Very similar to the mass degenerate case, but overall weaker limit on tanβ
- "Bump" around 660-860 GeV comes from clustering in `Higgsbounds`

Impact on the m_A-tanβ plane in the N2HDM





- Atlas four-top limit is stronger than the CMS limit
- Only applicable for the mass-degenerate case
- Atlas limit only on ttH-channel; not necessarily stronger when including tWH and tH-channels

Summary

Work done

- We generated and recasted Monte-Carlo events at CMS for four-top final states with a generic scalar X
- Validation of upper-limits on the cross-section times branching fraction and tanβ
- Implementation of upper-limits on the cross-section times branching fraction for CP-odd and CP-mixed in the public code `HiggsBounds`
- Study of the impact on a benchmark point in the N2HDM

Outlook

- Study in a model with CP-mxied states (C2HDM)