tH, ttH production at ATLAS and CMS

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Outline

- Introduction
- Elements for interpretation
- H Decay modes covered in this talk
- Description of the searches and their results

Introduction

- The Higgs coupling to top quarks is an important piece for understanding the Higgs physics
  - The direct way to access it in the LHC is though the ttH and tH production
    - Small production cross sections in comparison with the other production modes in the SM hypothesis
      - ggF ~ 43 pb
      - ZH/WH ~ 1.5 pb /1 pb
      - ttH ~ 500 fb
      - tHW ~ 70 fb
      - tHq ~15 fb

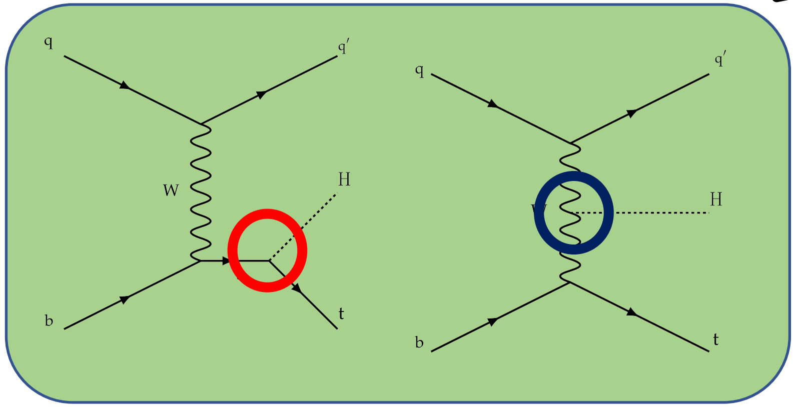
The ttH process was first observed using data from the 7 TeV, 8 TeV runs and partial luminosity of the 13 TeV data, combining several H final states, by ATLAS (Phys. Lett. B 784 (2018) 173) and CMS (Phys. Rev. Lett. 120, 231801 (2018))

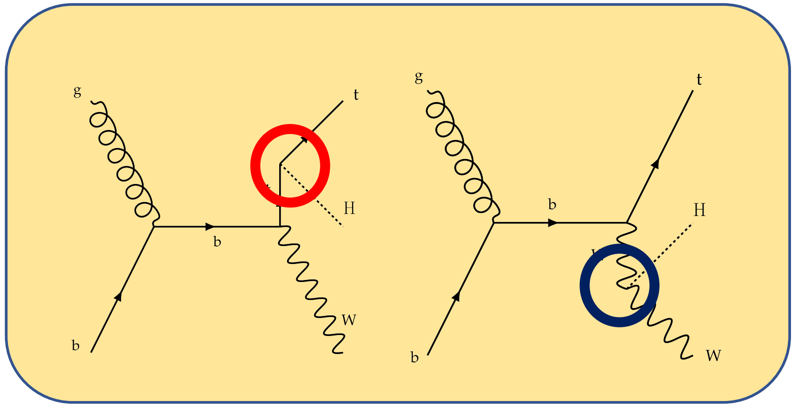
In this presentation we cover the analyses that consider full LHC run2 data and focus on the tH/ttH production modes

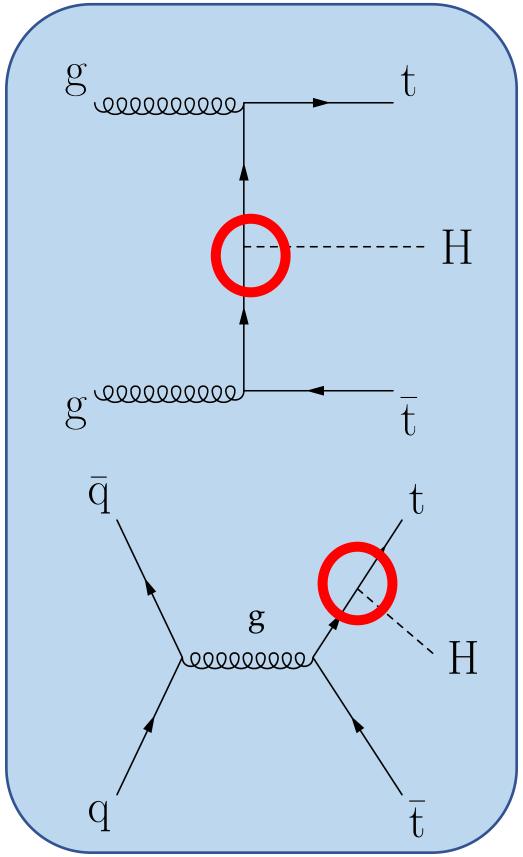
Elements for interpretation

- When a interpretation in terms of couplings is made, the kappa framework is used, sometimes extended with the CP phase definition

- Three kinds of processes can be considered
  - In the ttH
  - The tHq and tHW



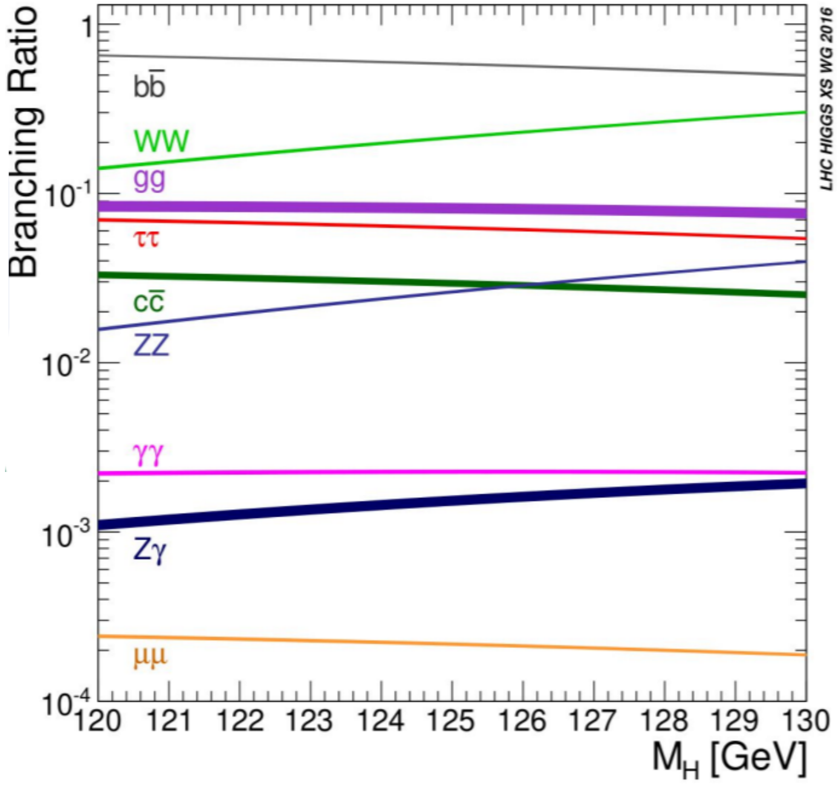




These entangle the effect of the Higgs boson coupling to top quarks (**kt**) and to gauge bosons (**kv**)

H Decay modes covered in this talk

- H →bb (ATLAS)
  - Largest Branching Ratio (BR), but also large backgrounds
- H → WW*/tt → multilepton (CMS)
  - Moderate backgrounds, intermediate BR
- H → γγ (ATLAS and CMS)
  - Smaller backgrounds, smaller BRs
    - Cleaner to probe the coupling structure



ttH →bb

HIGG-2020-23
arXiv:2111.06712 Submitted to JHEP

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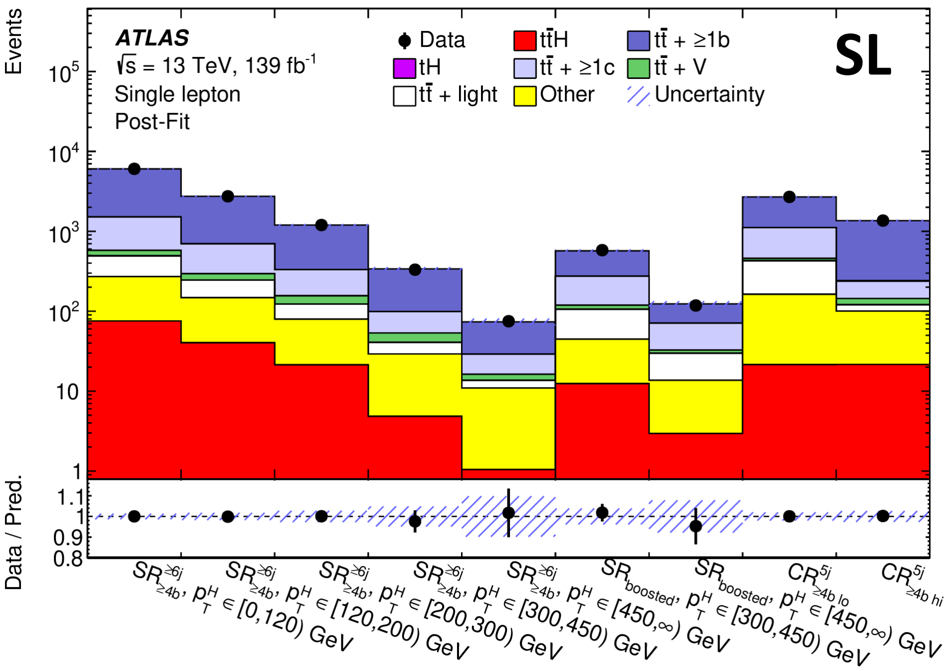
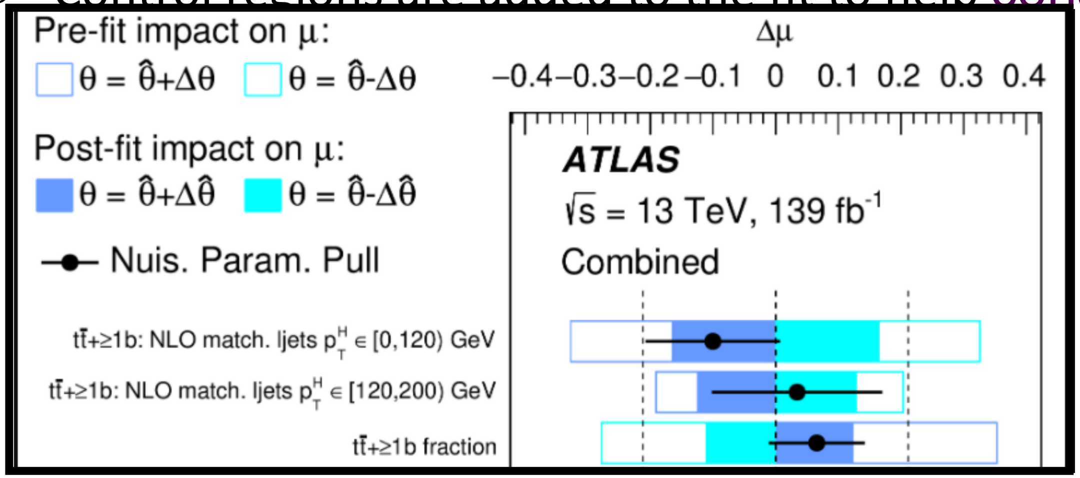
- To decrease the BKG rate only cases where one or two top quarks decay leptonically (e or μ)
- Categorization:
  - Number of leptons: Single-lepton (SL) and Double-lepton (DL)
  - Number of jets, b-jets and boosted Hbb candidates (for SL)
  - A further categorization in the reconstructed H pT (a la STXS) improves the sensitivity to BSM physics
- In some categories a BDT made to separate ttH signal and BKG, while in others a count experiment is done



- *tt* + jets events are categorized according to the flavor of additional jets in the event,
  - *tt* + jets modeling uncertainties limit analysis sensitivity
    - Control regions are added to the fit to help constrain it



ttH →bb

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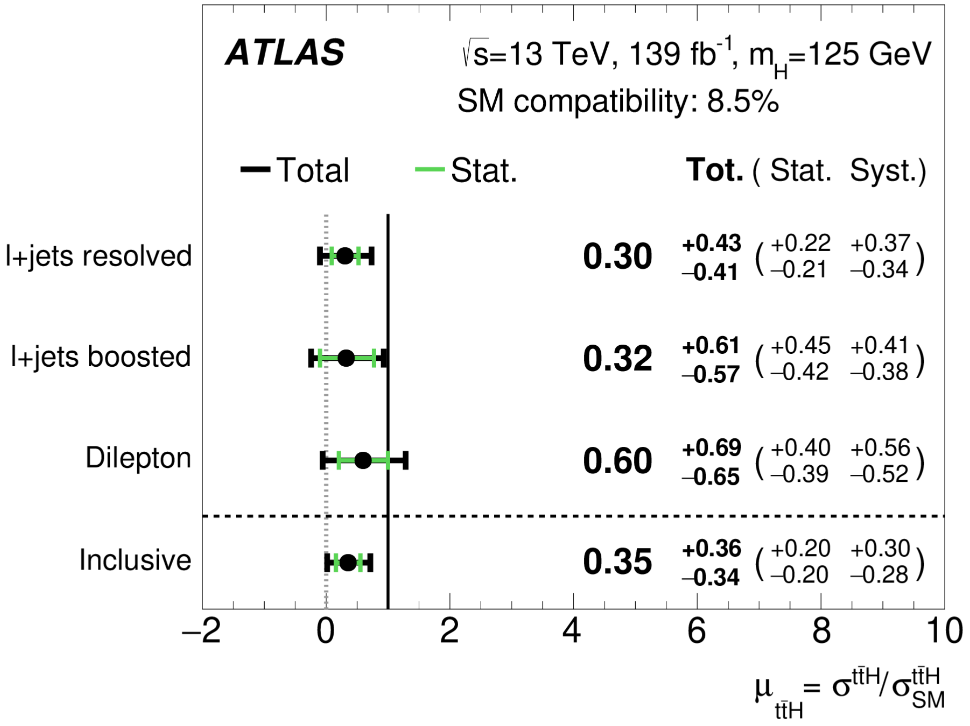
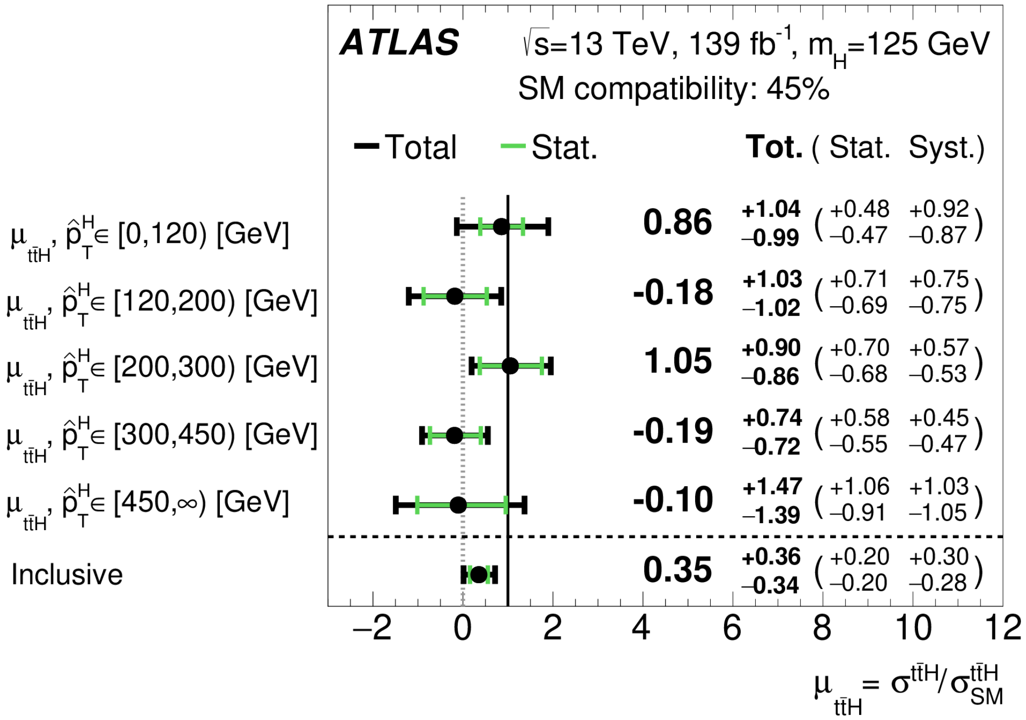
Results are produced as upper limits and signal strength constraints on the SM hyphothesis





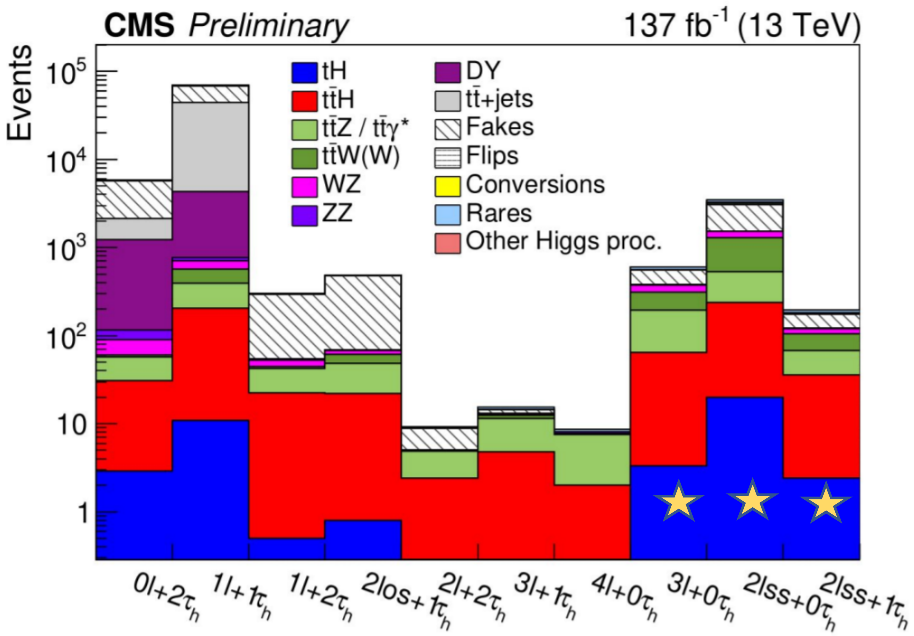
1.0 (2.7) σ observed significance on the ttH process, consistent with SM prediction

Constrain in the signal strength of the SM hyphothesis are produced also in H pT bins

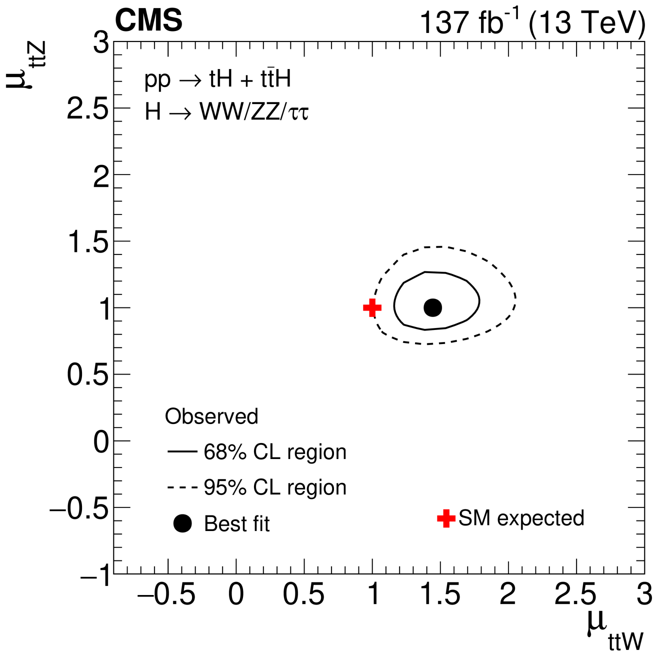
The same final state was analysed by CMS, with 41.5/fb of Run 2 data (HIG-18-030)

tH and ttH, H →WW*/ZZ*/ττ → multilepton

- Both the tHq and tHW productions are considered along with ttH
- Classification in the number of leptons (e or mu) and hadronic taus



- In the three most sensitive categories a DNN separates the tH, ttH signals and main BKGs in that region ( ) otherwhise a BDT is made to separate the ttH signal from BKG
  - Subcategorizations in terms of the lepton flavour and number of b-jets considered for when the DNN is used
- The output of the MVAs are used to fit the signal



- Three control regions are added to the fit, to constraint ttW, ttZ & ZZ BKGs
  - The normalization of those is left floating in the fit
    - An excess on the ttW normalization is found (*)

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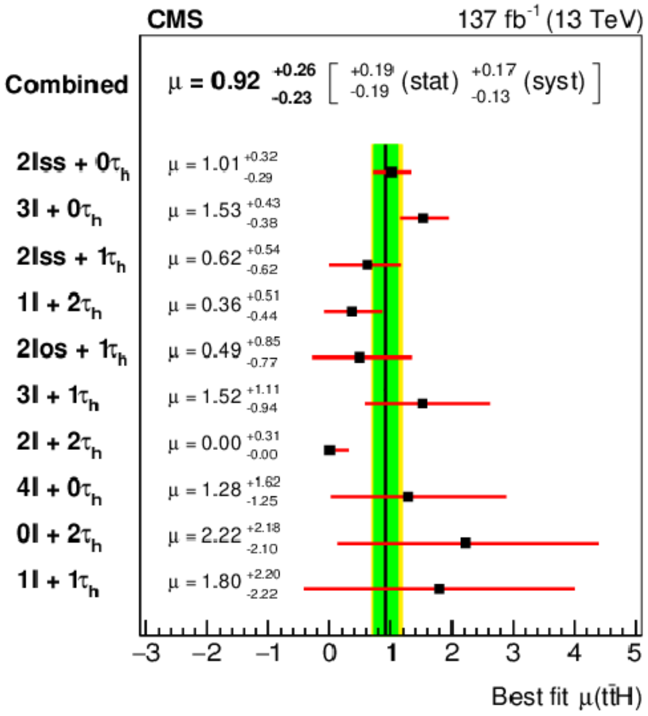
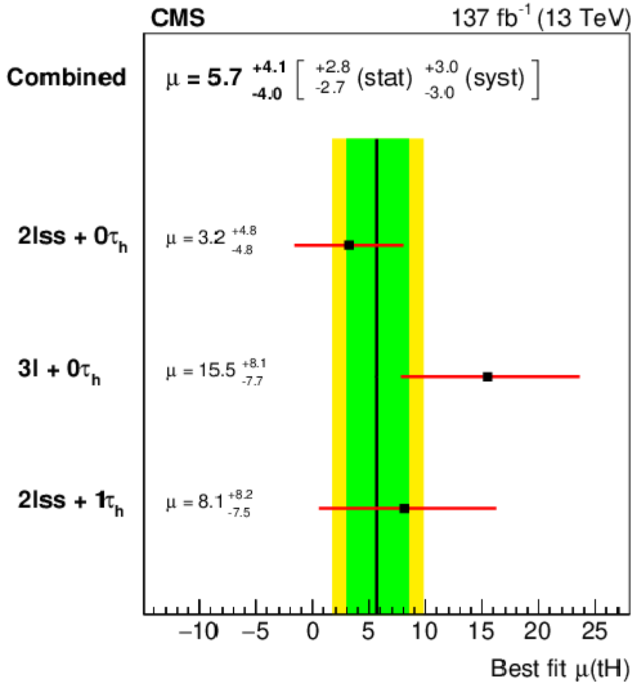
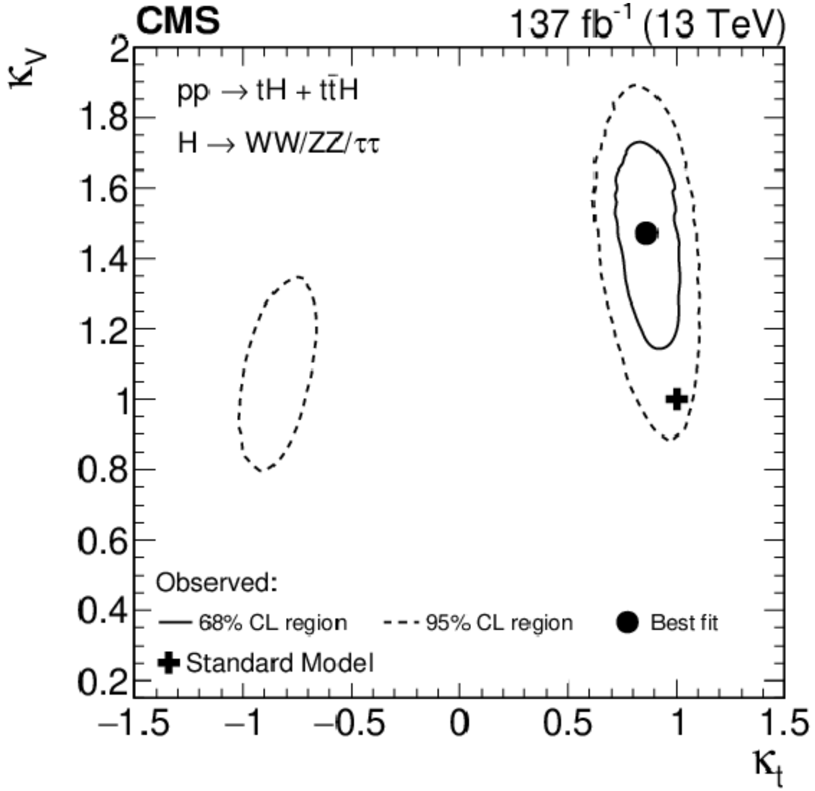
(*) Similar result is found on the analysis for same final state by ATLAS, with 80/fb of Run 2 data (ATLAS-CONF-2019-045)

tH and ttH, H →WW*/ZZ*/ ττ → multilepton

Results are produced both as signal strength constraints on the SM hyphothesis and on H coupling modifiers







4.7 (5.2) σ observed significance on the ttH process, consistent with SM prediction
κt is between [-0.9,0.7] [0.7, 1.1], at 95% confidence level.

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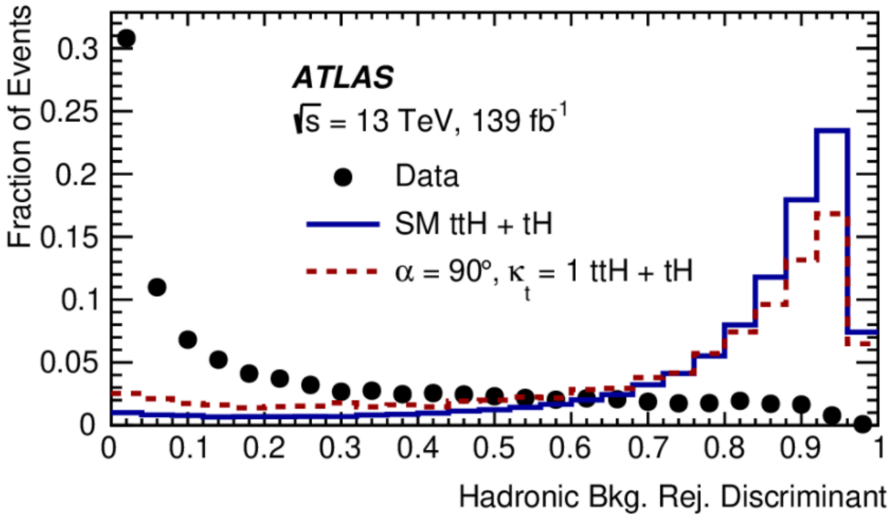
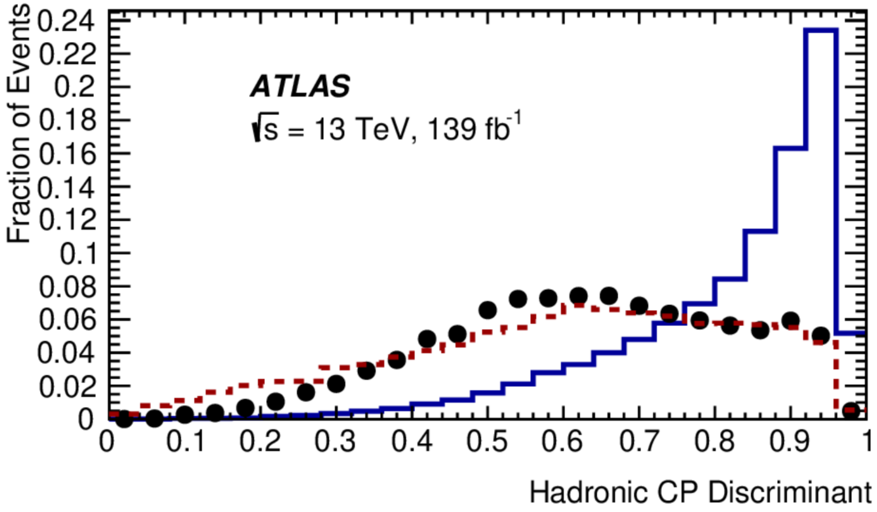
tH and ttH, H → γγ

- Both the tHq and tHW productions are considered along with ttH.
- Events are categorized between fully hadronic and when one at least one of the top quarks decay leptonically
- A BDT is used to reconstruct the two top quarks in each region
- This infomation serves as input to two other BDTs
  - One to separate the ttH signal from BKG
  - One to separate CP-even and CP-odd events for both ttH and tH signal
- Those last two BDTs are used to define 20 subcategories





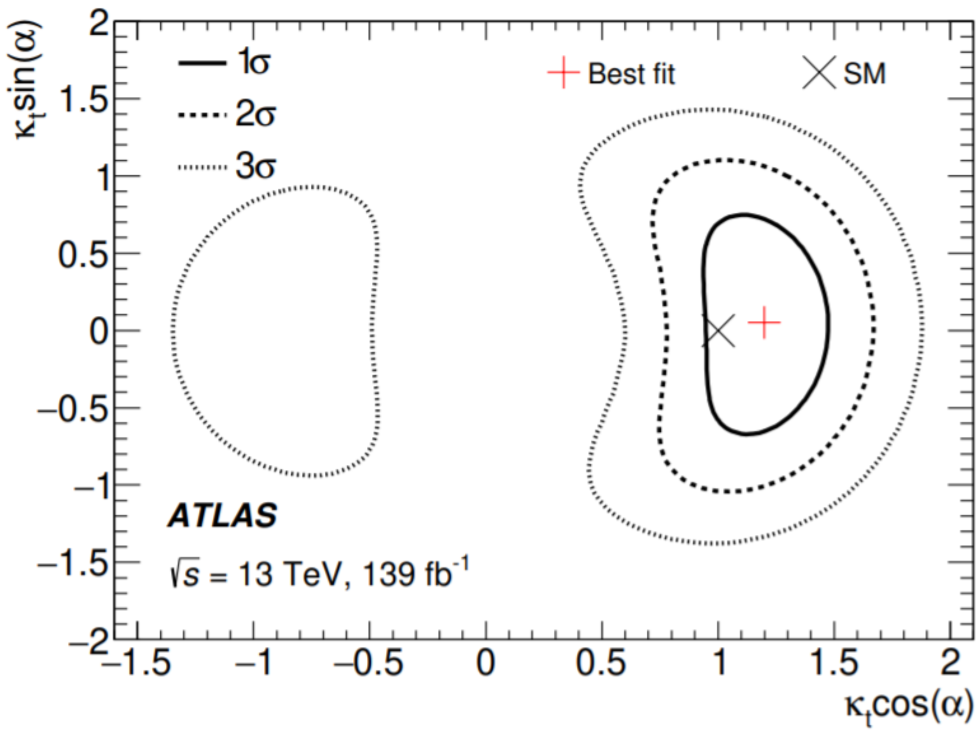
- The BKG estimation is data-driven and the signal extraction made with a fit on mγγ on each subcategory

[Phys. Rev. Lett. 125 (2020) 061802]

tH and ttH, $H \rightarrow \gamma\gamma$

Results are produced in terms of the product of kt and the sin/cos of the CP angle ⟶ $\mathcal{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t \kappa_t \left[\cos(\alpha) + i\sin(\alpha)\gamma_5\right]\psi_t\right\} H$

- The kv couplings is assumed as in SM

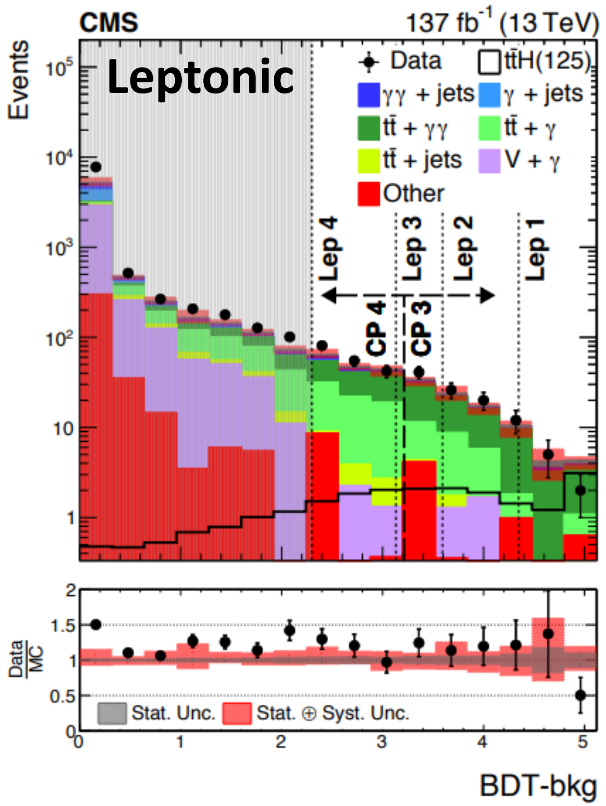


5.2 (4.4) σ observed significance on the ttH process, consistent with SM prediction
An upper limit of 12 times the tH signal as in SM is set
Alpha > 43° is excluded at 95% CL
Pure pseudo-scalar CP structure of the t-t-H coupling is excluded with 3.9 (2.5) σ significance

Phys. Rev. Lett. 125 (2020) 061802

ttH, H → γγ

- Events are categorized between fully hadronic and when one at least one of the top quarks decay leptonically
- A BDT is made to sepatare the ttH signal from BKG
  - This is used to subcategorize the events, optimizing OR the significance to the ttH as in SM OR the expected sensitivity of the CP structure of the t-t-H coupling, depending on the interpretation of the result being considered
- The BKG estimation is data-driven and the signal extraction made with a fit on mγγ on each subcategory



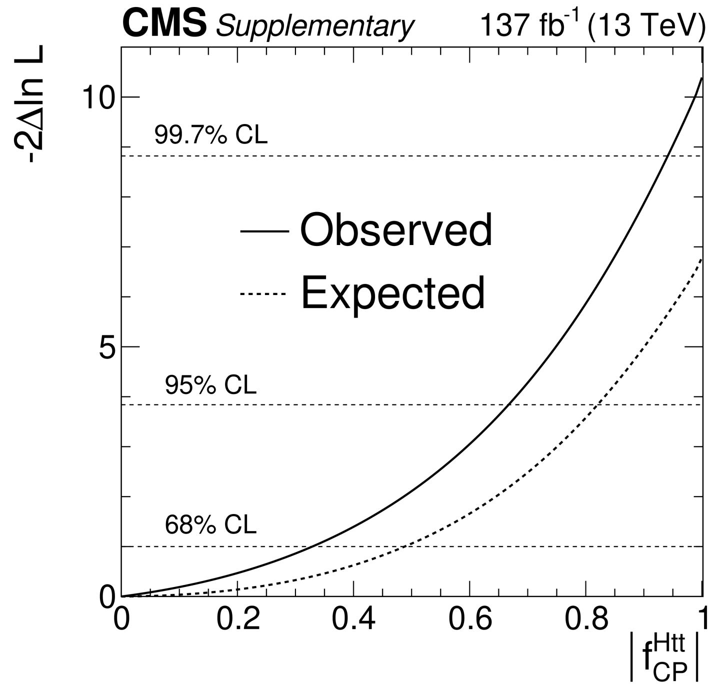
Results in terms of the CP structure

$$\mathcal{A}(\mathrm{Htt}) = -\frac{m_t}{v}\bar{\psi}_t\left(\kappa_t + i\tilde{\kappa}_t\gamma_5\right)\psi_t,$$

$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t)$$

6.6 (4.7) σ observed significance on the ttH process, consistent with SM prediction

Pure pseudo-scalar CP structure of the t-t-H coupling is excluded with 3.2 (2.6) σ significance



HIG-19-013

PRL 125 (2020) 061801

Further results that will also interest this audience

Other results with full run 2 luminosity combining the different H production modes, that also features the ttH and tH processes on the results

- ATLAS result combining several H decay modes (ATLAS-CONF-2021-053)

- ATLAS result on H → ZZ* → 4l (Eur. Phys. J. C 80 (2020) 957)
- Results on H → γγ, that also contains STXS measurements
  - ATLAS: ATLAS-CONF-2020-026
  - CMS: JHEP 07 (2021) 027

Conclusions

The analyses with the full run2 luminosity of the LHC targeting the tH, ttH processes were presented

- Different aspects of the process are explored
  - The ATLAS analysis considering H → bb also constrains the signal strength differentially
  - The CMS analysis considering H →WW*/ZZ*/ ττ → multilepton considers the tH and ttH production modes and explore its effect on constraining the t-t-H and V-V-H couplings simultaneouslly
  - Both the ATLAS and CMS analyses considering H → γγ observe alone the ttH signal, and also probe the CP structure of the t-t-H coupling

All the results are compatible with the SM

Backup

ttH →bb

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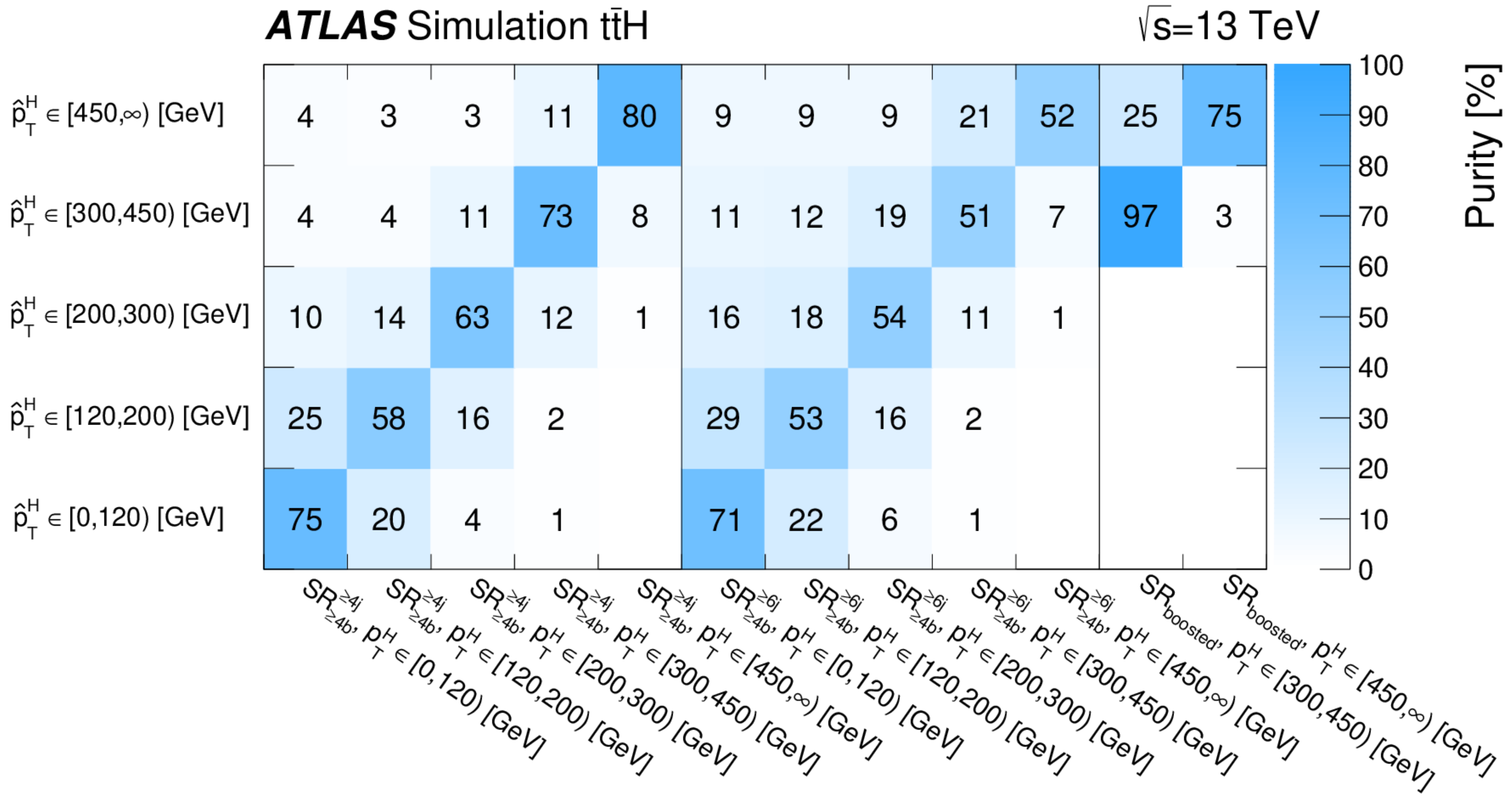
Performance of the Higgs boson reconstruction algorithms. For each row of `truth' $\hat{p}_T^H$, the matrix shows (in percentages) the fraction of all Higgs boson candidates with reconstructed p_T^H in the various bins of the dilepton (left), single-lepton resolved (middle) and boosted (right) channels



ttH →bb

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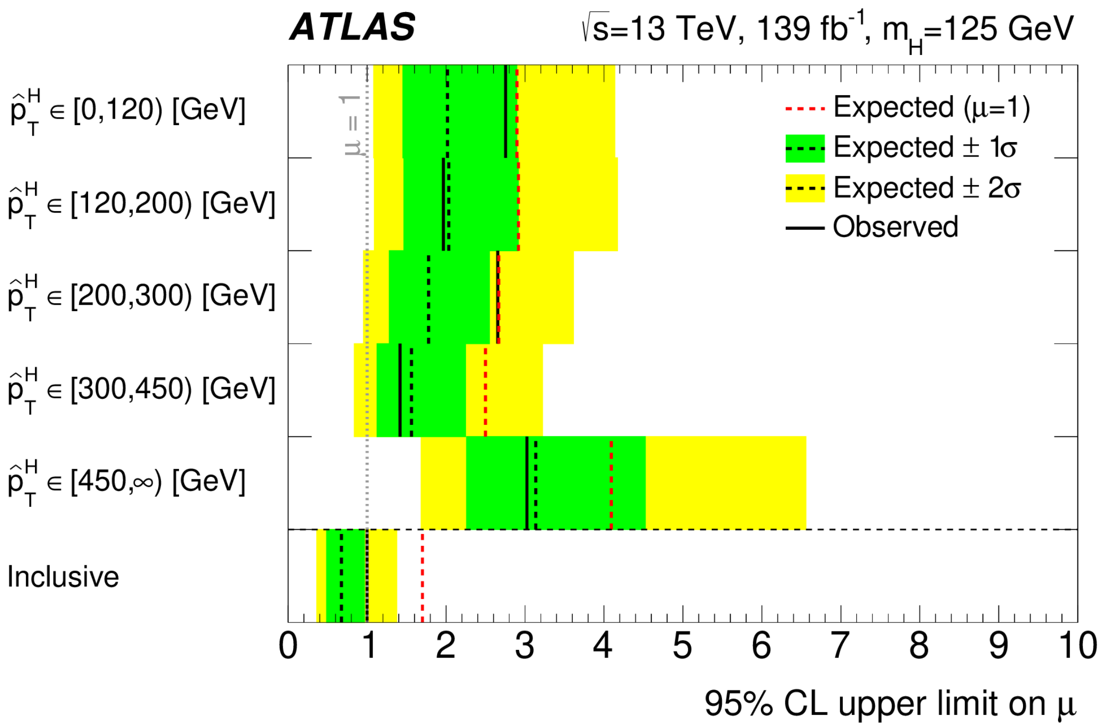
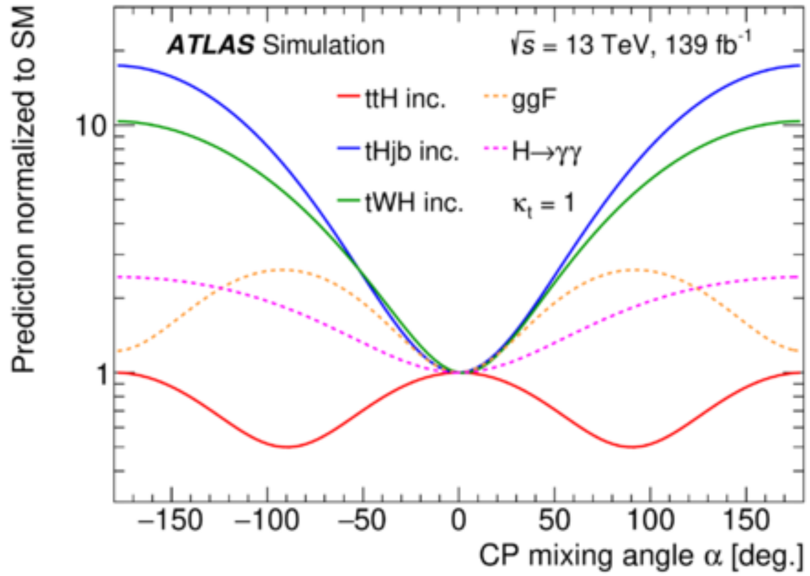
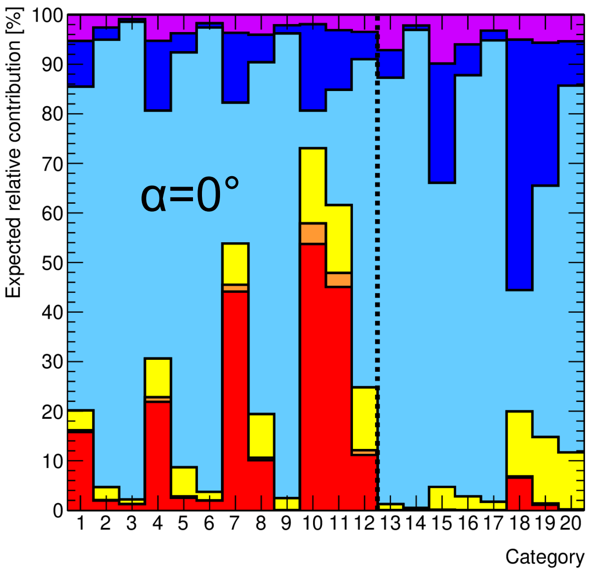
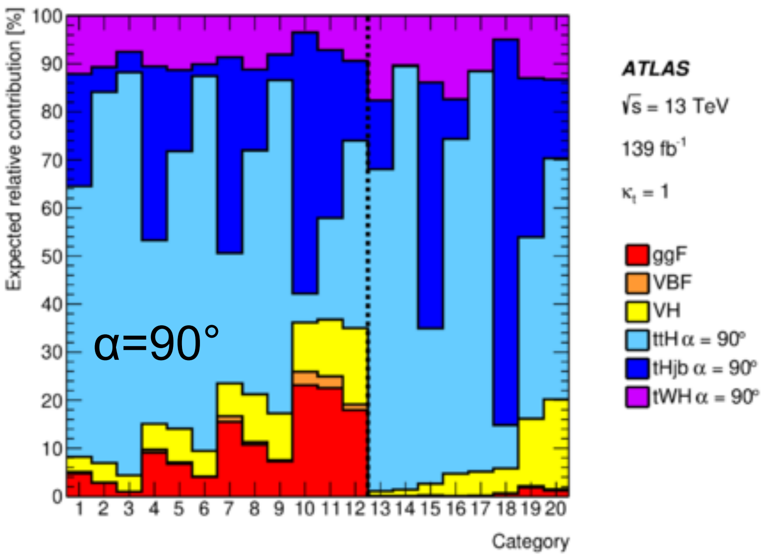


tH and ttH, H → γγ

- Signal composition



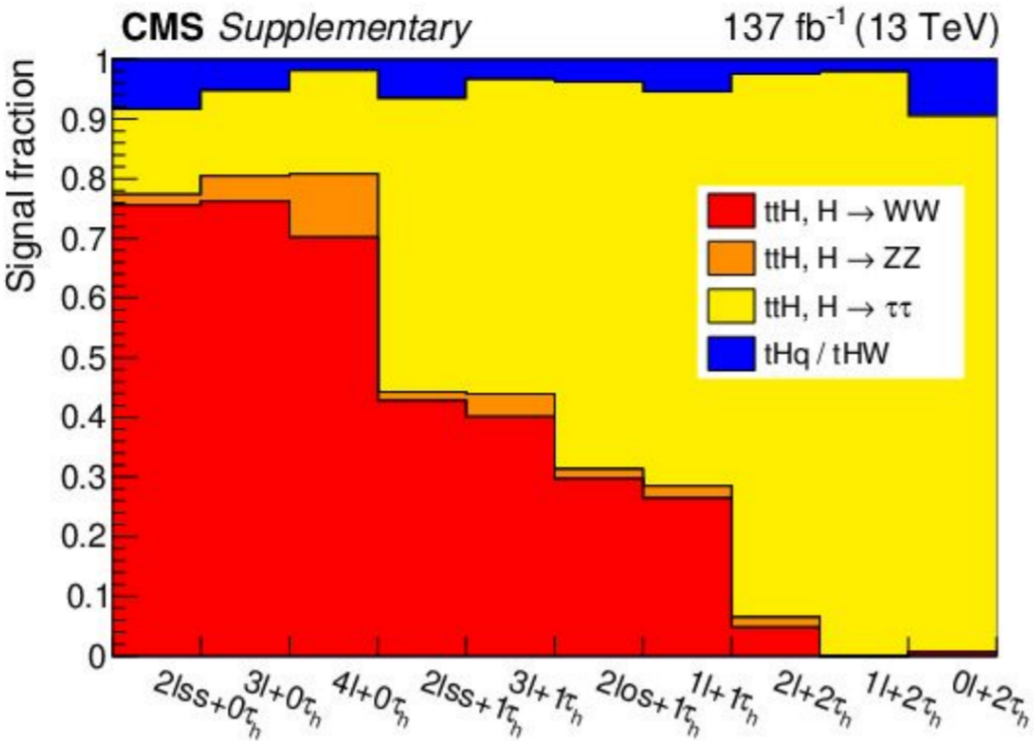




[Phys. Rev. Lett. 125 (2020) 061802](#)

tH and ttH, H →WW*/ZZ*/tt → multilepton

- Results in terms of categories and signal composition



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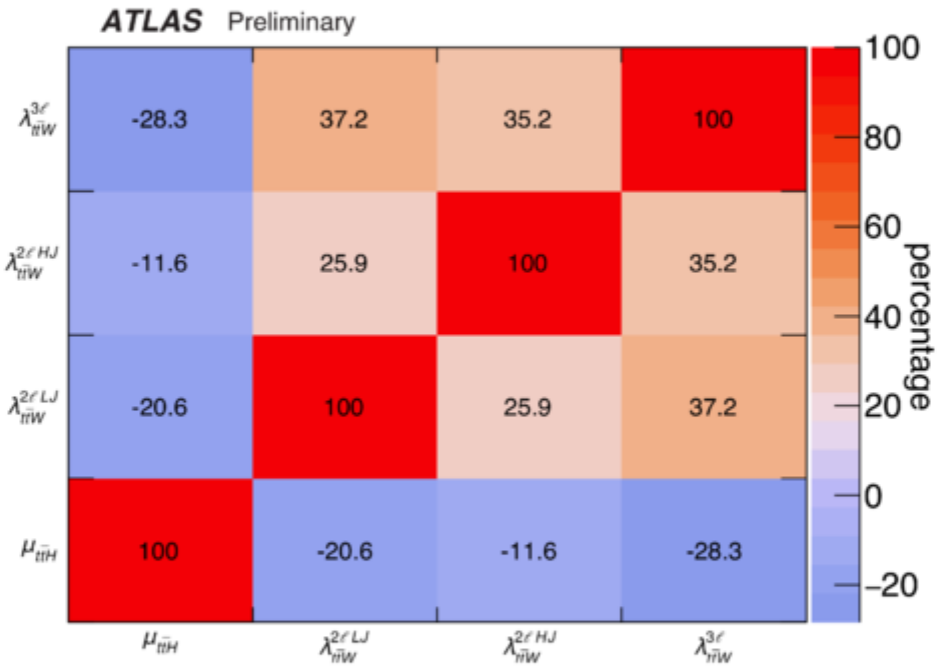
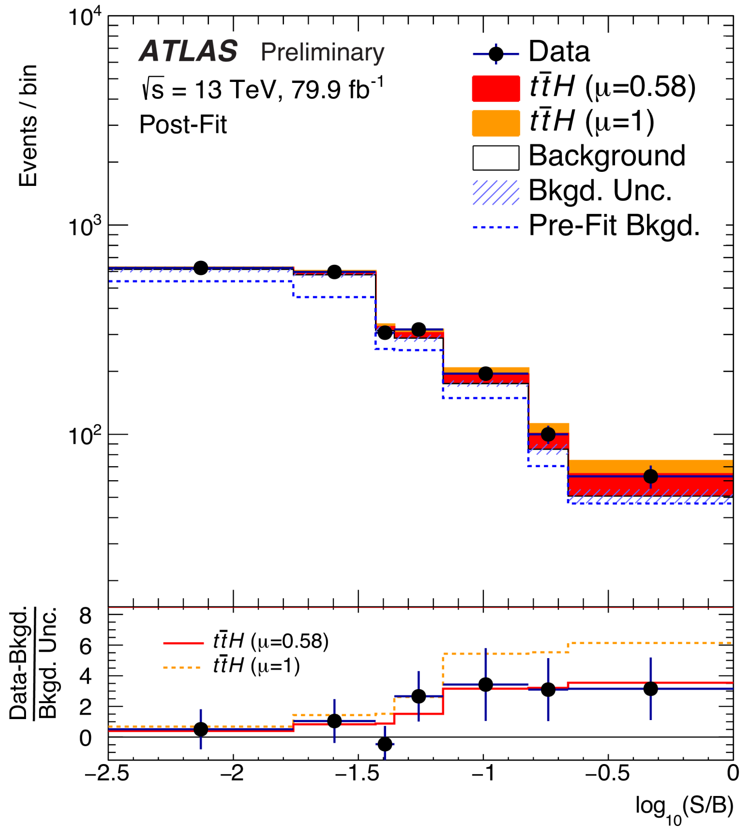
tH and ttH, H →WW*/ZZ*/ ττ → multilepton



Observed correlations between the signal strength μ and the normalisation factors for the tt̄W background in the profile likelihood fit to the data.



The ttH process is observed as in SM with 1.8 (3.1) σ significace
A significance of 1.4 (0.3) σ is found to the tH signal as in SM