Measurements of the ttH + tH production with the CMS detector

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on behalf of the CMS collaboration

LHCP 2024
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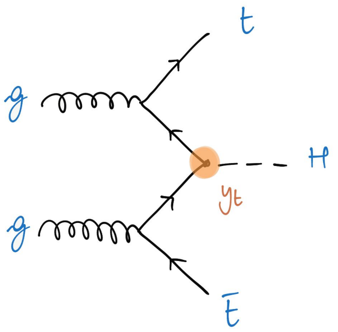
Outline

- Introduction on ttH and tH processes
- ttH ($H \rightarrow \gamma\gamma$)
- ttH+tH multilepton
- ttH ($H \rightarrow bb$)
- ttH ($H \rightarrow bb$) EFT

Why measuring ttH…?

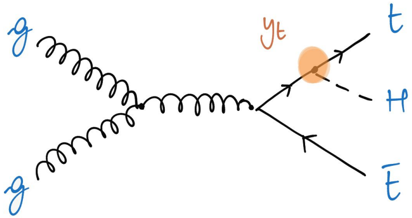
The ttH production process is a direct probe of the top-Higgs interaction…



- Access to the top-Higgs Yukawa coupling y_t
- The top quark has the largest Higgs-fermion coupling in the SM ($y_t^{SM} \approx 1$)
- y_t has a crucial role in the stability of the electroweak vacuum
- Sensitive to new physics

… and a challenging process to observe due to its rarity

- **Cross section:** ~507 fb at $\sqrt{s}$ = 13 TeV (@ NNLO)



It was first observed by ATLAS and CMS in 2018, combining several channels

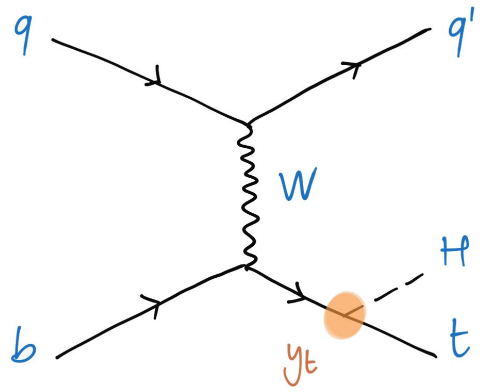
CMS result: 5.2σ (4.2σ exp.) with Run 1 + 35.9 fb^{-1} Run 2

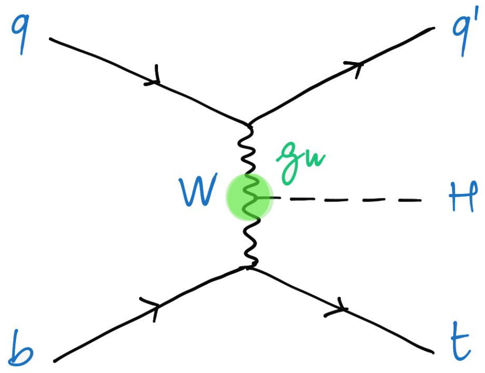
Phys. Rev. Lett. 120 (2018) 231801

… and tH?

The tH production is also an important probe of the top-Higgs interaction

- Sensitive to the relative sign of y_t and g_W
- Enhancement of cross section up to 10× in the inverted top coupling scenario
- tH final state is orthogonal to ttH





tH is even more rare than ttH

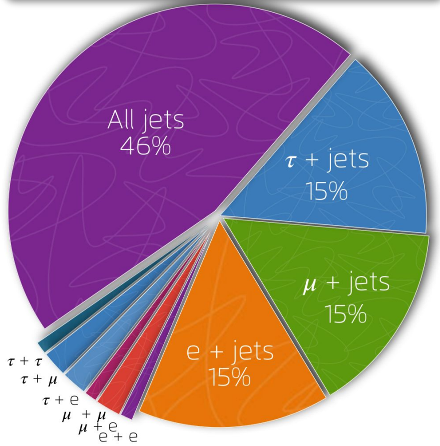
- Cross section: ~90 fb at $\sqrt{s}$ = 13 TeV
- No evidence yet in CMS data

Measurements overview

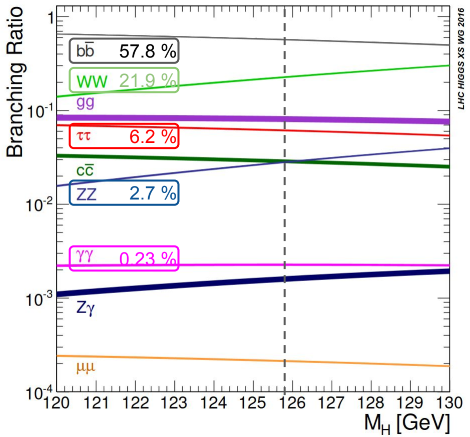
ttH/tH analyses span a wide range of final states

- Several combinations of top and Higgs decays
- Many possible final states including several different particles
  - → jets, b-tagging, leptons, photons, MET
- Accurate modeling of backgrounds is crucial

Top pair branching ratios



Higgs decay modes



Covered in this talk:

ttH ($H \to \gamma\gamma$) Run 2
Phys. Rev. Lett. 125 (2020) 061801
JHEP 07 (2021) 027

ttH multilepton Run 2
Eur. Phys. J. C 81 (2021) 378

ttH ($H \to bb$) Run 2
CMS-PAS-HIG-19-011
Phys. Rev. D 108 (2023) 032008

ttH (H → $\gamma\gamma$) – Differential measurements

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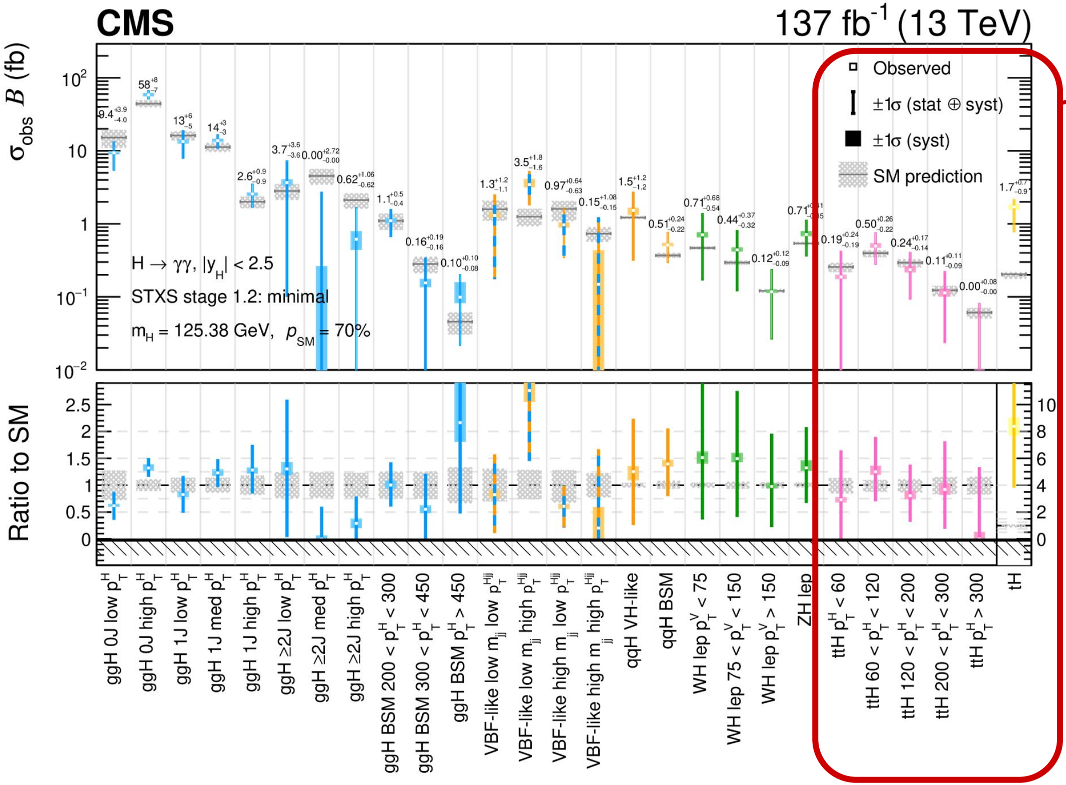
Categorization in STXS bins based on $p_T(\gamma\gamma)$

STXS = Simplified Template Cross Sections

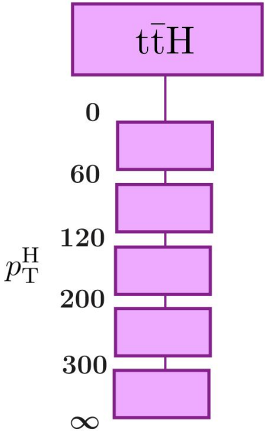


ttH+tH categories from STXS H→ $\gamma\gamma$ combination

- Same categorization as in the inclusive measurement
- 5 STXS bins for ttH
- One STXS bin for tH

tH signal strength

$$\mu_{tH} = 8^{+3}_{-5}$$



ttH (H → $\gamma\gamma$)

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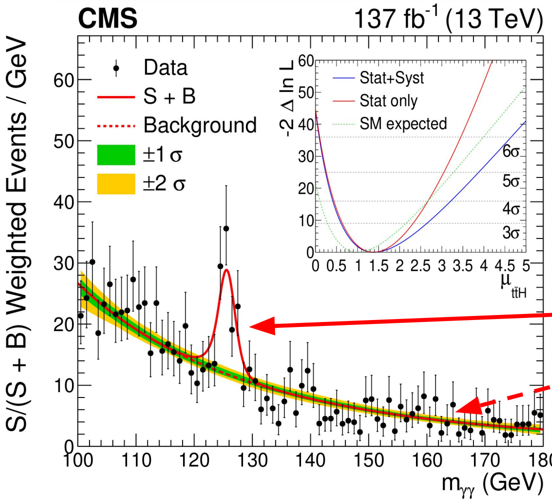
H → $\gamma\gamma$ provides a clear signature

- Reconstruct Higgs boson from pairs of photons in ECAL
- Exploit outstanding mass resolution (1%)

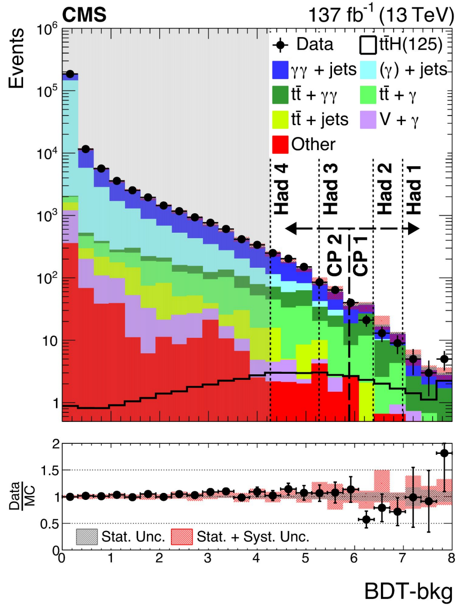
Fit to diphoton mass distribution and likelihood scan for μ_{ttH}



Analysis strategy

- Events divided into **leptonic** and **hadronic** channels
- BDT discriminants for each channel
  → maximise sensitivity to CP and μ_{ttH}
- Simultaneous fit to $m_{\gamma\gamma}$
  → **Signal:** Gaussian + Crystal-Ball
  → **Background:** analytic function

BDT distribution for signal extraction in hadronic channel



ttH (H → $\gamma\gamma$) – Results

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First observation in single-Higgs decay channel with full Run 2

Significance: 6.6σ (4.7σ exp.)

$$\mu_{t\bar{t}H} = 1.38^{+0.36}_{-0.26} = 1.38^{+0.29}_{-0.27}\,(\text{stat})^{+0.21}_{-0.11}\,(\text{syst})$$

$$\sigma_{t\bar{t}H}\mathcal{B}_{\gamma\gamma} = 1.56^{+0.34}_{-0.32} = 1.56^{+0.33}_{-0.30}\,(\text{stat})^{+0.09}_{-0.08}\,(\text{syst})\text{ fb}$$

First measurement of CP structure of Htt vertex

Pure CP-odd coupling excluded at 3.2σ (2.6σ exp.)

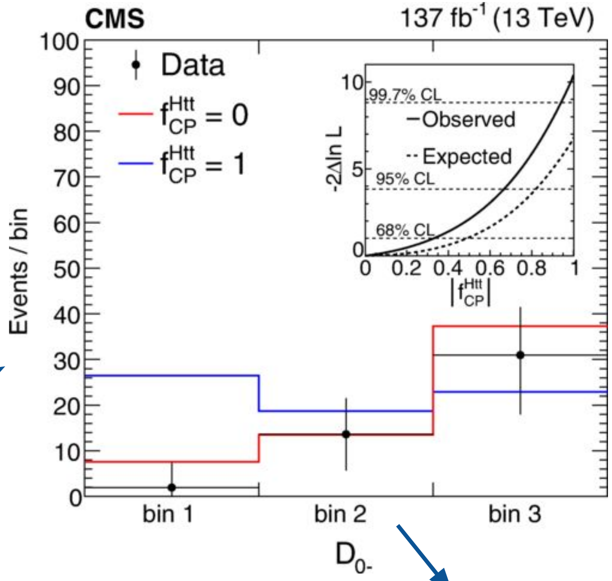
$$f_{CP}^{Htt} = 0.00 \pm 0.33$$

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

=0 in the SM

=1 if pure CP-odd coupling

Events in bins of the D_{0-} observable and likelihood scan for f_{CP}^{Htt}



extracted via BDT regression

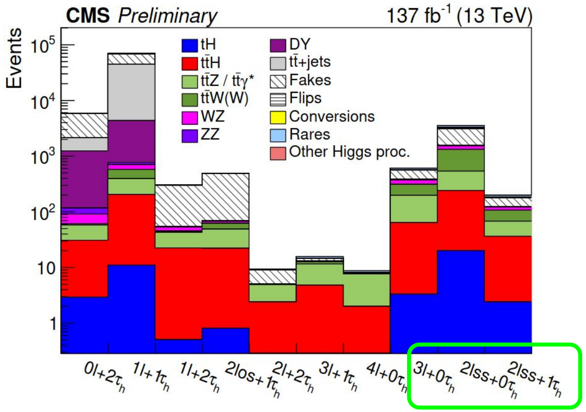
ttH multilepton

[Eur. Phys. J. C 81 (2021) 378]

Analysis targeting H → WW/ZZ/$\tau\tau$ decay channels

- Multitude of final states including e/μ leptons and hadronic τ
- Dedicated categories sensitive to tH production
- First simultaneous measurement of ttH and tH

Process contribution per category

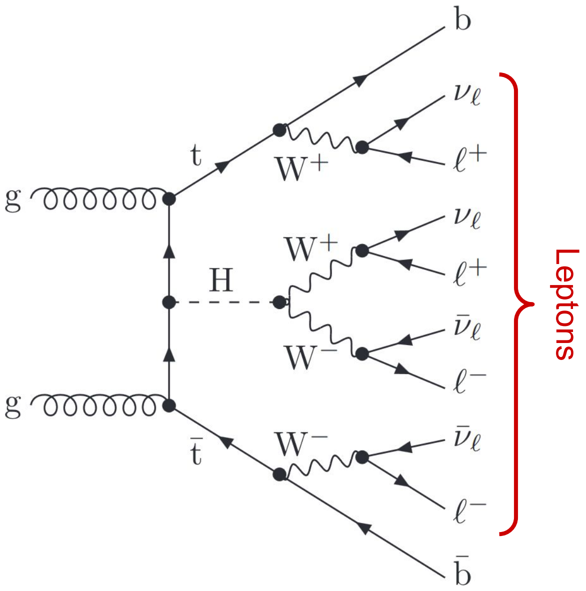


tH enriched categories

Challenging background estimation:

- Irreducible:
  ttW, ttZ/gamma, diboson
- Reducible:
  non-prompt or **fake leptons**

Example diagram for ttH with H→WW decay

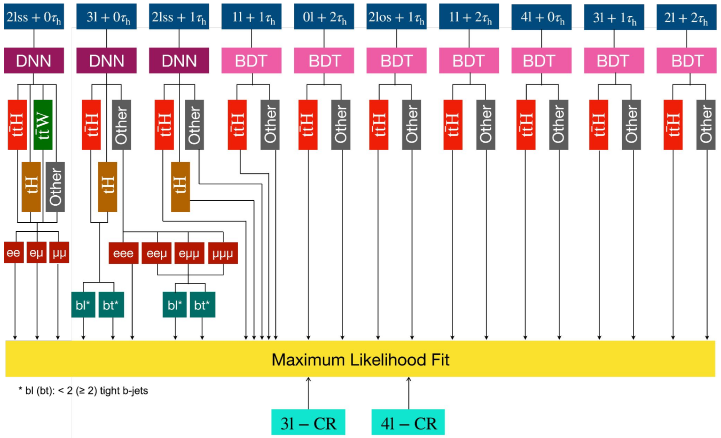


ttH multilepton – Analysis strategy

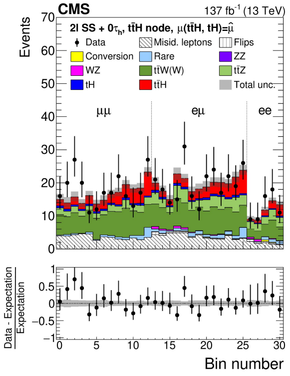
Eur. Phys. J. C 81 (2021) 378

- **10 event categories** based on
  → lepton flavour, multiplicity and electric charge
- Signal extraction with
  → **DNN** in tH enriched categories
  → **BDT** in other categories
- 3 control regions to constrain ttW and ttZ backgrounds
- Simultaneous fit of signal and control regions

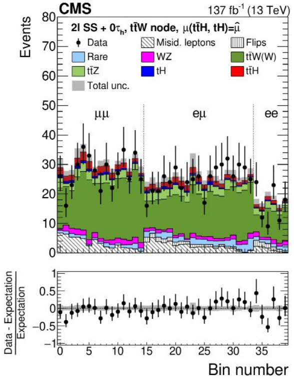
Categorization strategy used for signal extraction



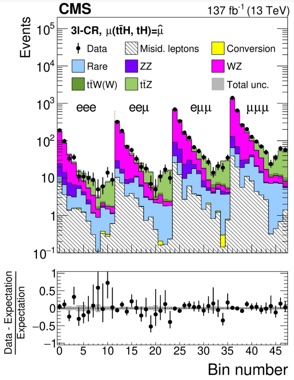
Signal region

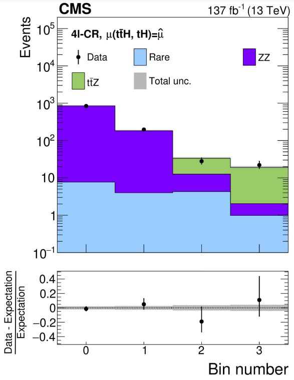


ttW(W) control region



ttZ control regions





ttH multilepton – Results

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Significance **ttH**: 4.7σ (5.2σ exp.) **tH**: 1.4σ (0.3σ exp.)

ttH and tH signal strength

$$\mu_{t\bar{t}H} = 0.92 \pm 0.19\,(\mathrm{stat})^{+0.17}_{-0.13}\,(\mathrm{syst})$$

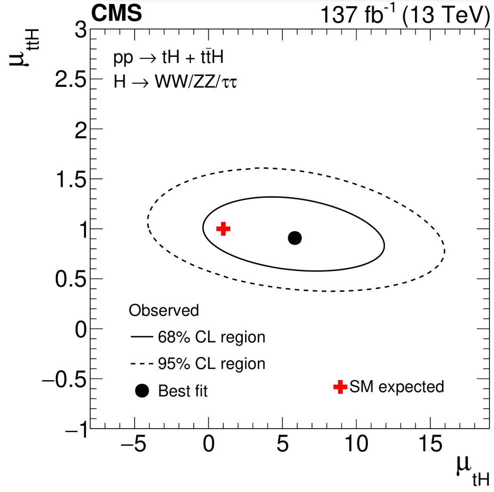
$$\mu_{tH} = 5.7 \pm 2.7\,(\mathrm{stat}) \pm 0.3\,(\mathrm{syst})$$

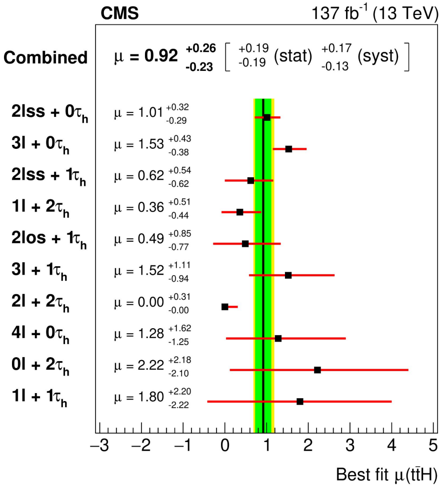
Constraint on κ_t coupling modifier

$$-0.9 < k_t < -0.7 \quad \text{or}$$

$$0.7 < k_t < 1.1 \quad \text{at 95\% C.L.}$$

2D likelihood contours for μ_{ttH} and μ_{tH}





Production rate per channel and combined

ttH (H → bb)

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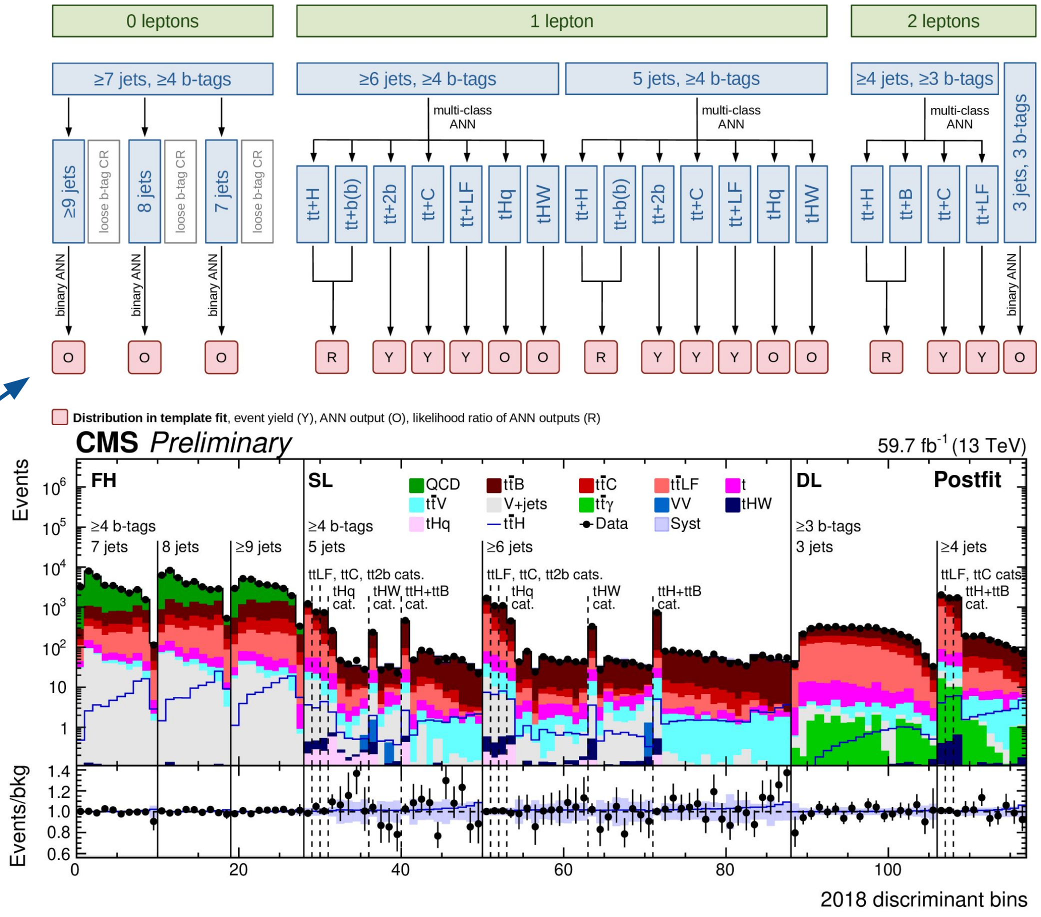
Higgs decay channel with highest BR

- Ambiguity in assignment of jets to the Higgs candidate
- Irreducible **tt+bb background**

  → difficult to model

Complex analysis strategy

- Categories in lepton, jet and b-jet multiplicity
- BDT for jet-parton assignment
- Signal extracted using DNN multi-classifiers
- Simultaneous fit of discriminant scores



Postfit yields in each discriminant

ttH (H → bb) – tt+bb background

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tt+bb is the irreducible background

- Difficult to model and to measure
- Simulations underpredict cross-section by ~20-30%
- Data/MC differences in relevant distributions

Two approaches to simulate events:

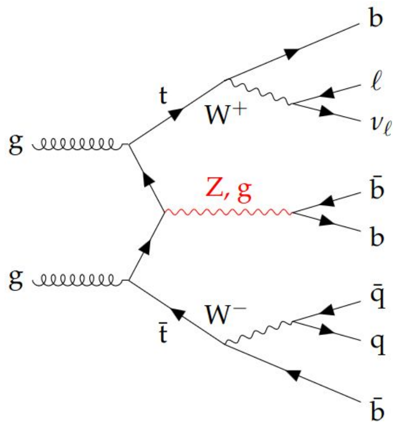
- tt ME @NLO + PS g→bb splitting (5FS)
- ttbb ME @NLO (4FS)

ME: matrix element, PS: parton shower, FS: flavour scheme

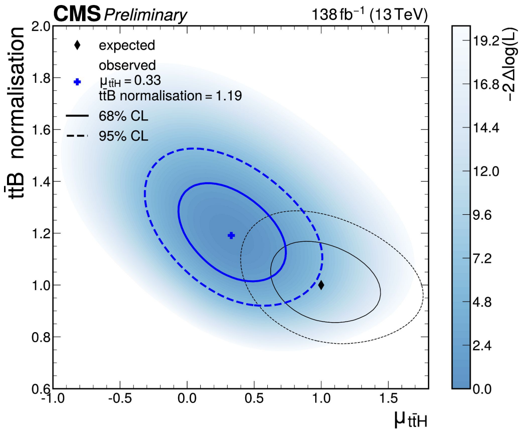
tt+bb background joint simulation:

- ttbb Powheg 4FS
- tt inclusive Powheg 5FS
- Overall tt+bb normalization freely-floating

Example diagram for tt+bb



2D likelihood scan for μ_{ttH} and ttB background normalisation



Background normalisation

$$t\bar{t}B \text{ norm.} = 1.19 \pm 0.13$$

ttH (H → bb) – Results

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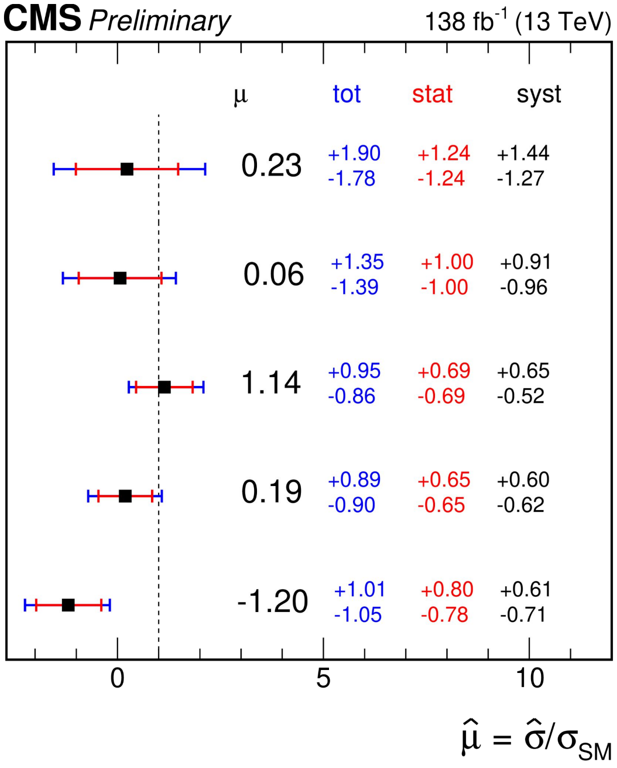
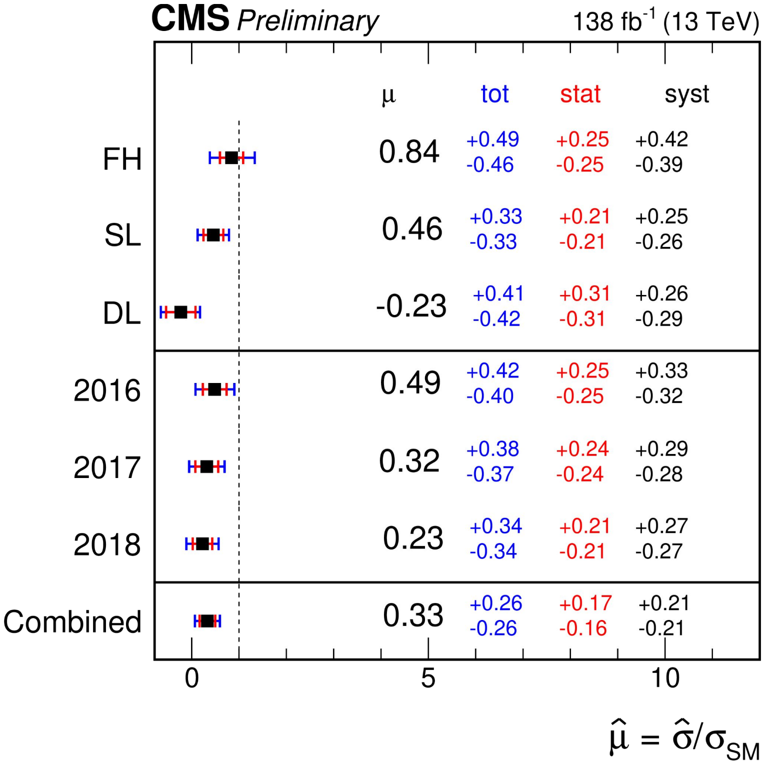
Measured μ_{ttH} in STXS bins



Dominated by systematic uncertainties

Measured μ_{ttH} split by channel and year



0 leptons

1 lepton

2 leptons

Significance: 1.3σ (4.1σ exp.)

ttH (H → bb) – EFT

Phys. Rev. D 108 (2023) 032008

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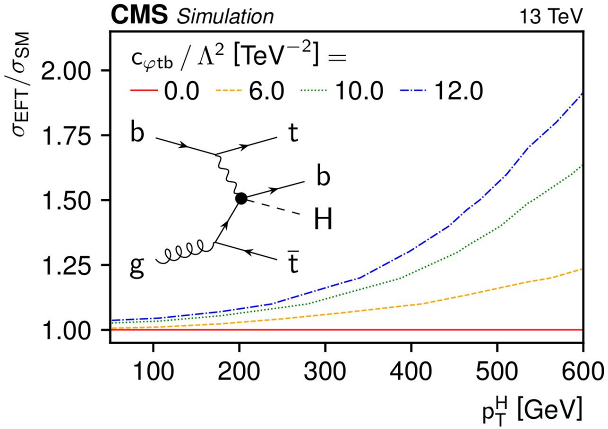
=0 for lepton number conservation

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Standard Model EFT Lagrangian

SM EFT cross-section as a function of Higgs pT and $c_{\varphi tb}$



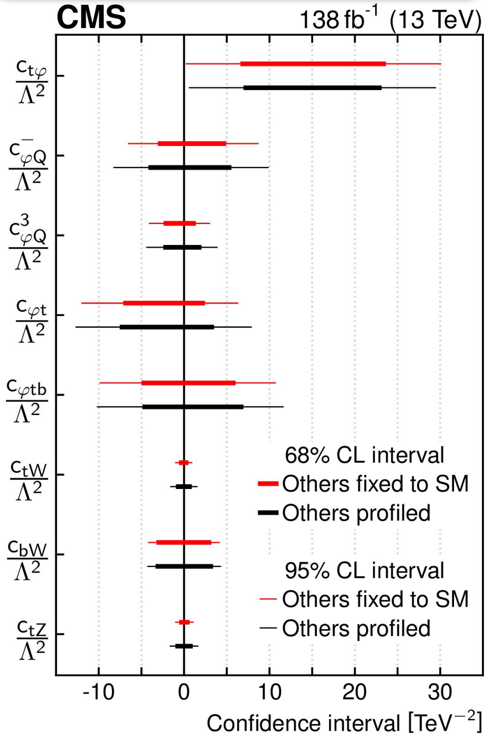
- Targeting ttZ + ttH in boosted topology
- DNN discriminant to select X→bb AK8 jets
- Constraints on 8 Wilson Coefficients of dim-6 operators relevant to ttH and ttZ

All measured Wilson Coefficients are compatible with the SM

First constraint of EFT parameters in ttH (H → bb)

See more in Suman's talk!

68% and 95% CL intervals for 8 Wilson Coefficients



Summary

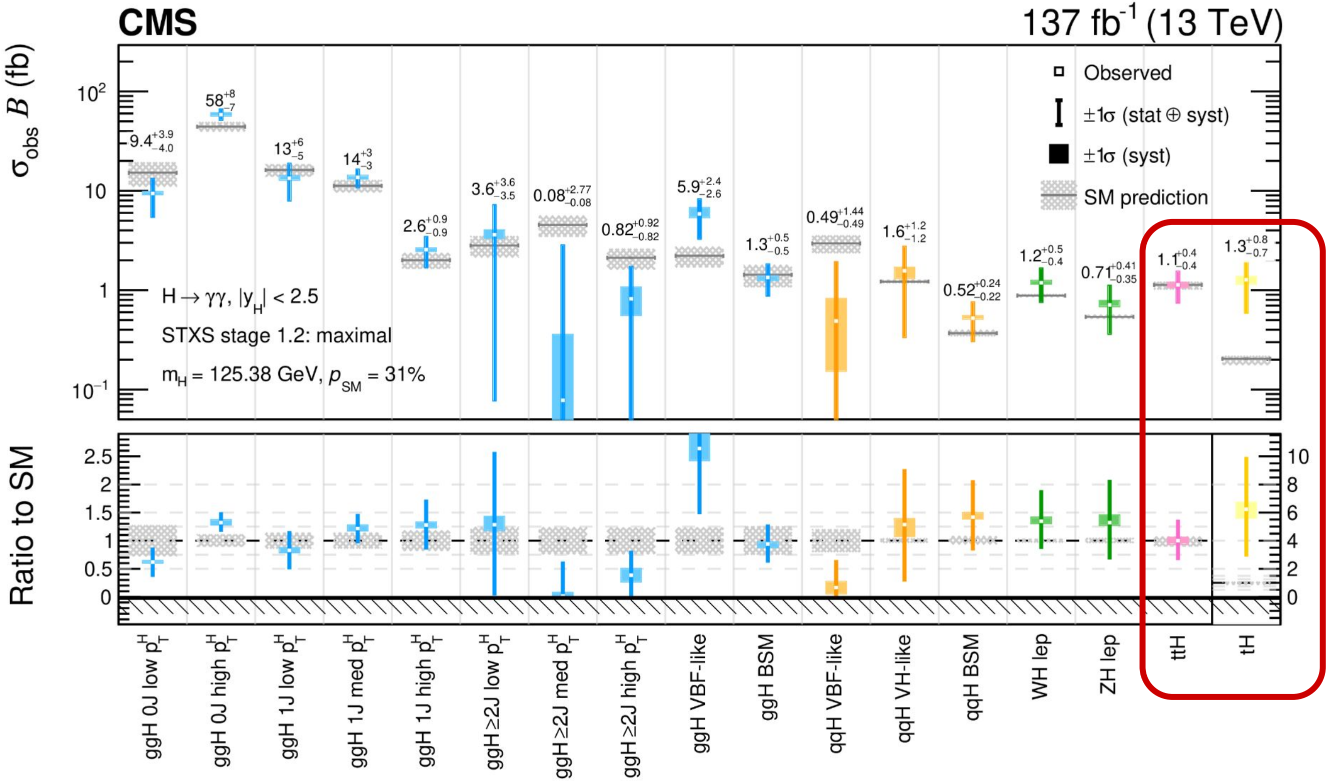
- Plethora of analyses targeting the ttH final state
  - → ttH ($H \rightarrow \gamma\gamma$), ttH multilepton, ttH ($H \rightarrow bb$)
- Very challenging measurement due to small cross section and complex final states
  - → ML-based strategies are fundamental
- Good precision of inclusive ttH results
- First differential results and analysis of CP structure in ttH+tH
- Observations are overall compatible with the SM

A lot was learnt in Run 2, looking forward to apply new ideas in Run 3!


Thank you for
the attention!

ttH (H → γγ) – STXS results

JHEP 07 (2021) 027



Observed results of the maximal merging scheme STXS fit

ttH+tH categories from STXS H→ γγ combination

ttH ($H \to \gamma\gamma$)

Phys. Rev. Lett. 125 (2020) 061801

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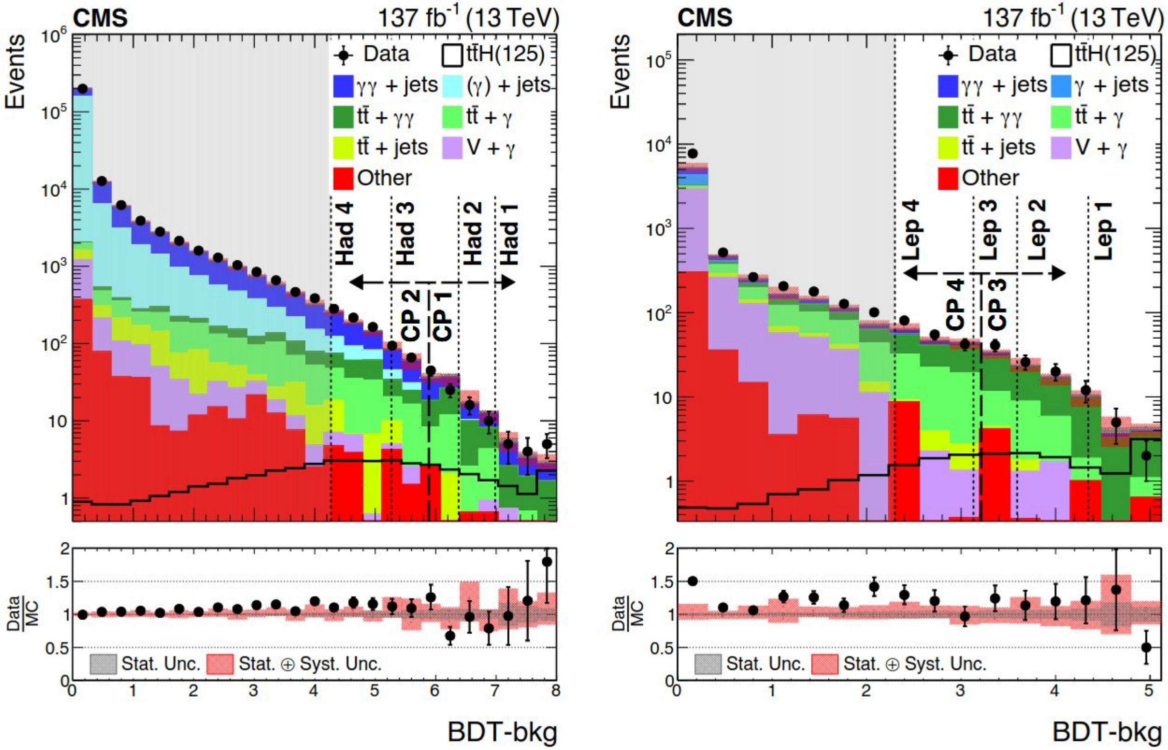

Distributions of BDT-bkg output used for event categorization,
for the hadronic (left) and the leptonic (right) channels.

ttH multilepton – Background normalisation

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ttZ and ttW signal strength

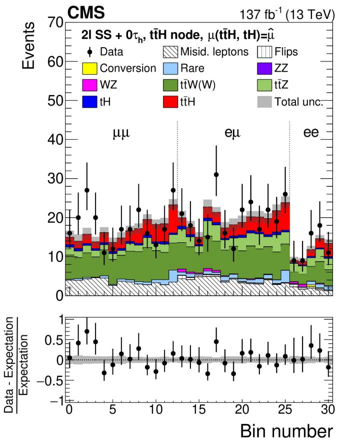
$$\mu_{t\bar{t}Z} = 1.03 \pm 0.14 \;(\text{stat} + \text{syst})$$

$$\mu_{t\bar{t}W} = 1.43 \pm 0.21 \;(\text{stat} + \text{syst})$$

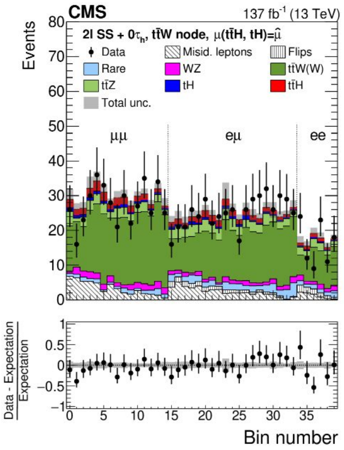
ttZ normalisation compatible with SM

ttW 2σ above SM

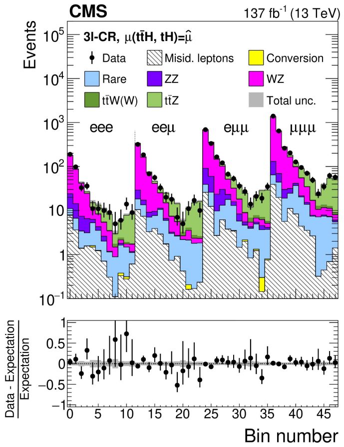
Signal region

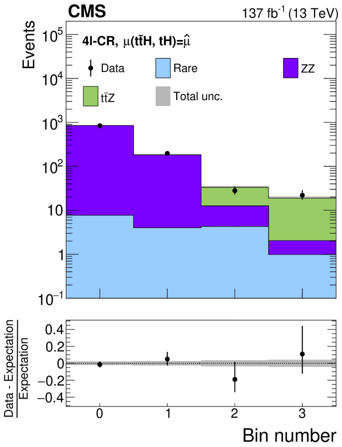


ttW(W) control region



ttZ control regions





ttH (H → bb)

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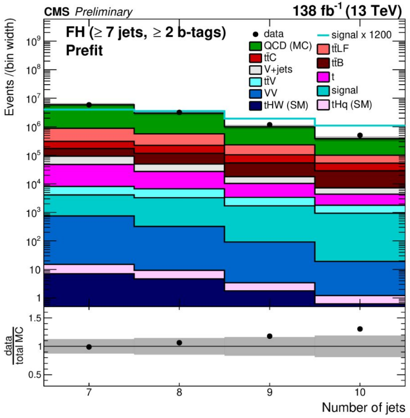

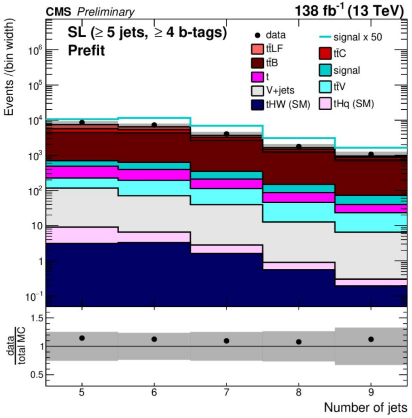

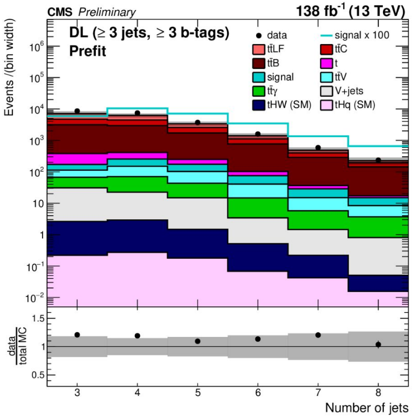

Prefit distributions of the jet multiplicity in the FH, SL and DL channels

ttH – CP properties

CMS-PAS-HIG-19-011
JHEP 07 (2023) 092

2D likelihood scan as a function of κ_t and $\tilde{\kappa}_t$ for
ttH multilepton and ($H \rightarrow \gamma\gamma$) (left) and ttH ($H \rightarrow bb$) (right)