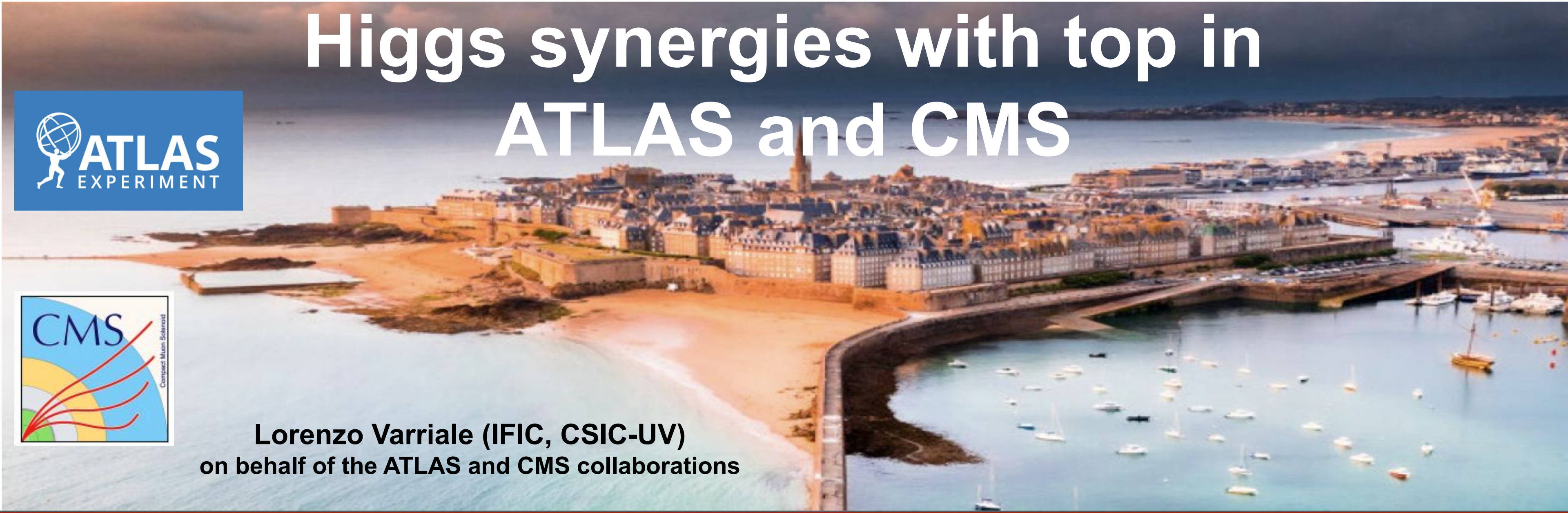
Higgs synergies with top in ATLAS and CMS

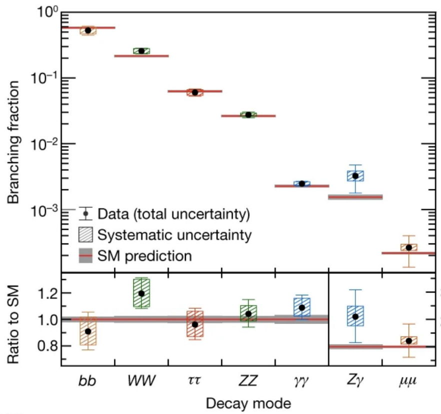


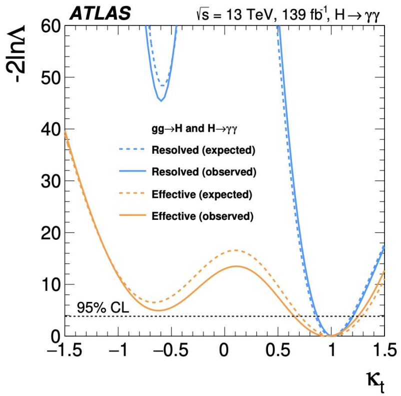
Lorenzo Varriale (IFIC, CSIC-UV)

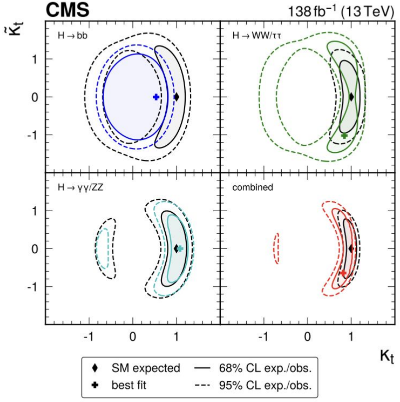
on behalf of the ATLAS and CMS collaborations

Talk outline

- **Why tt̄H/tH?**
- **Measuring tt̄H/tH**
- **Run 2 ATLAS and CMS measurements:**
  - tt̄H → bb
  - tt̄H → $\gamma\gamma$
  - tt̄H → multilepton
- **Why CP studies?**
- **Run 2 CP studies:**
  - H → $\gamma\gamma$ (ATLAS)
  - H → WW, H→ $\tau\tau$ (CMS)
  - H → bb (ATLAS & CMS)
- **Summary & conclusions**





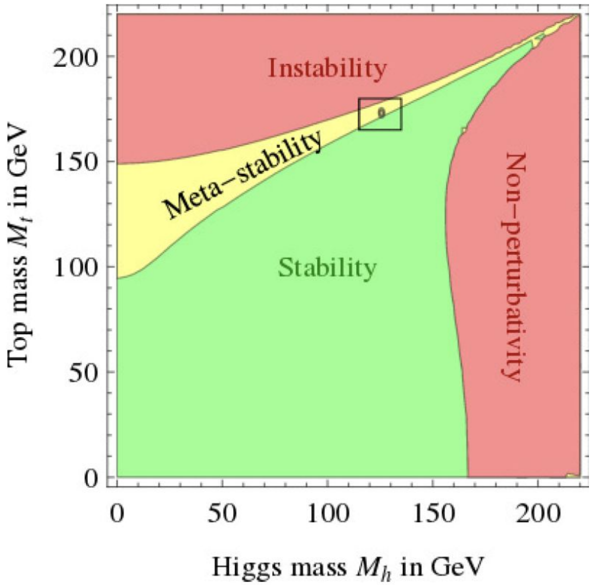


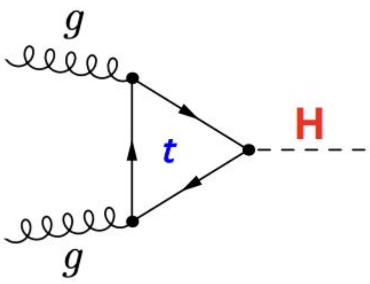
Top-Higgs boson synergies

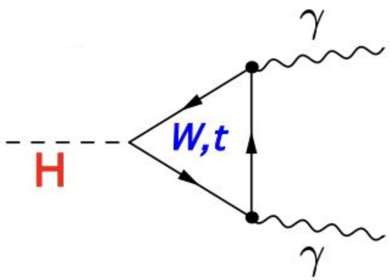
Top-Higgs relation central for multiple reasons

https://link.springer.com/article/10.1007/JHEP08(2012)098

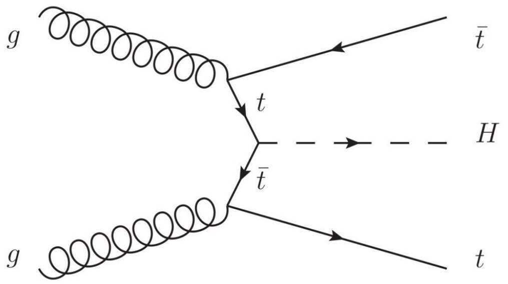
- Connection between top and Higgs masses has a crucial role in the stability of the electroweak vacuum
  - at the borderline of the stability of the electroweak vacuum on top mass - Higgs mass plane
- Yukawa coupling Higgs-fermions proportional to fermions mass:
  - top-Higgs is largest coupling in the SM ($\lambda_t \approx 1$)
  - cannot be observed directly in Higgs decays
  - contributes to ggF and H → γγ decays: could be used to determine λ_t but under model assumptions





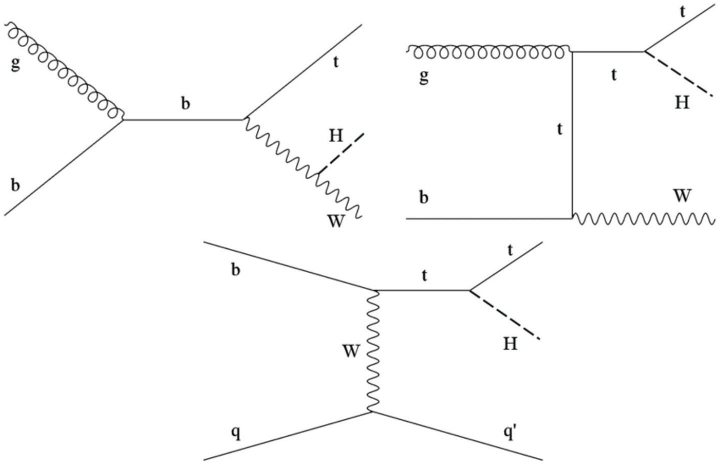


Why measure tt̄H and tH?



- **tt̄H** production is a direct probe of the top-Higgs interaction:
  - direct measure of top-Higgs Yukawa coupling λ_t
  - tree-level process with cross-section proportional to λ_t^2
  - sensitive to BSM effects

Observed by ATLAS [Phys. Lett. B 784 (2018) 173] and CMS [Phys. Rev. Lett. 120 (2018), 231801] in 2018

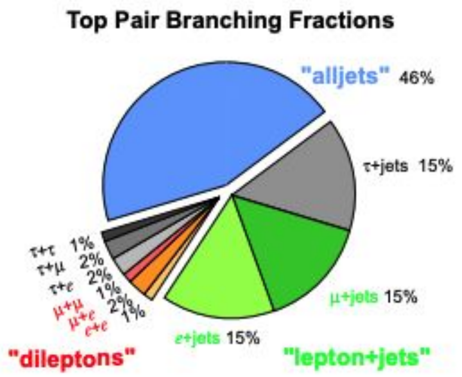


- **tH** production subdominant but other important probe of the top-Higgs interaction:
  - information regarding sign of λ_t
  - final state orthogonal to tt̄H

- No evidence/observation found neither in ATLAS nor in CMS
- An upper limit of ten times the SM prediction set in $H \rightarrow \gamma\gamma$ analysis
  - most stringent experimental constraint on tH production

Measuring tt̄H and tH

- Not easy to measure
- Production channels with low cross-sections
  - ttH: ~0.5 pb at √s = 13 TeV (@ NNLO)
  - tH: ~an order of magnitude lower (~0.09 pb)
- Rely on multiple analyses:
  - diverse decays of both top and Higgs
  - many objects involved (leptons, jets, etc…)



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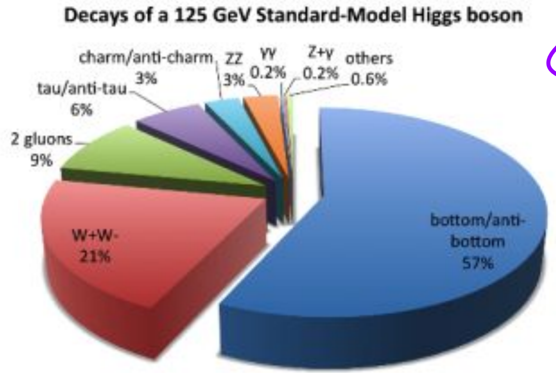
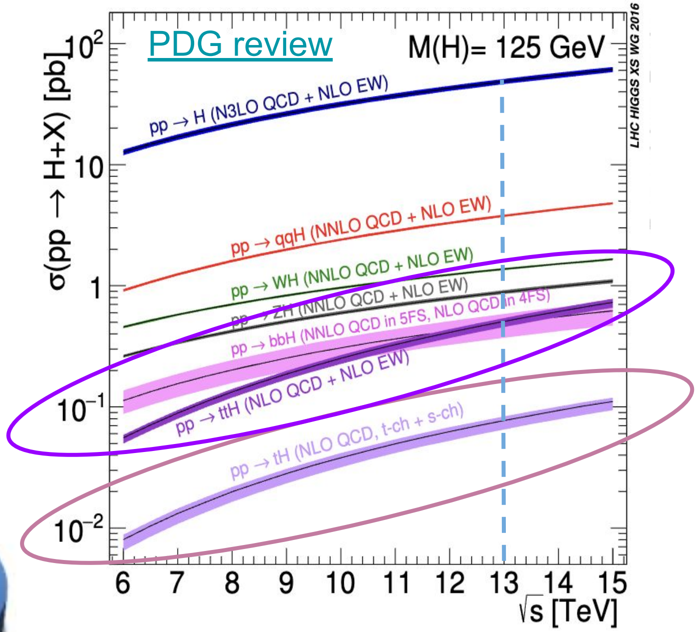
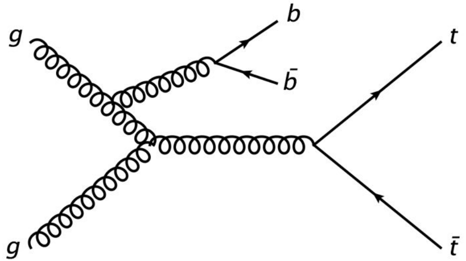


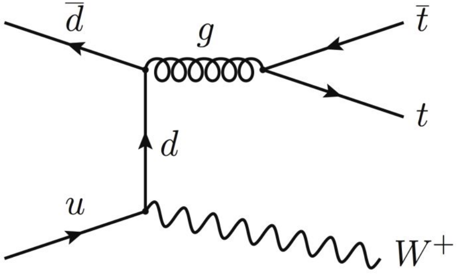


- Results usually expressed in terms of signal strength $\mu = \sigma/\sigma_{SM}$ or coupling modifier κ_t

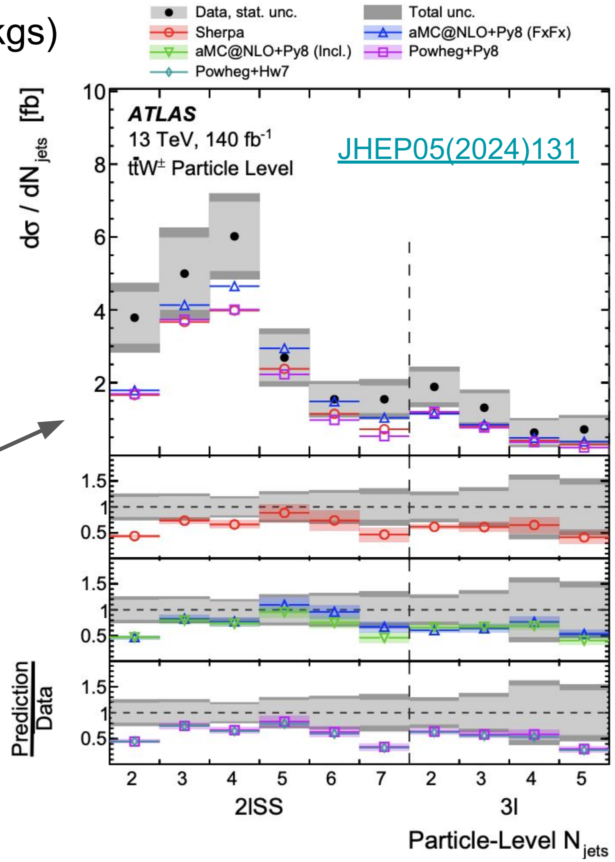
Main issue: modelling of $t\bar{t}bb$ and $t\bar{t}W$ processes

- Searches limited by modelling uncertainties of **$t\bar{t}bb$** and **$t\bar{t}W$** (main bkgs)





- Previous results from ATLAS & CMS measured higher cross sections than the state-of-the-art predictions
  - cross-section measured in data higher than theoretical predictions (bigger at low jet multiplicities)
  - predictions at high multiplicities with additional partons using NLO are in better agreement with data than NLO+PS Powheg prediction
- LHC Higgs and Top WG efforts to improve this
- Common MC modelling note on ttbb and ttW published by the Higgs cross-section WGs: arXiv:2301.11670



$t\bar{t}H/tH$ Run 2 analyses

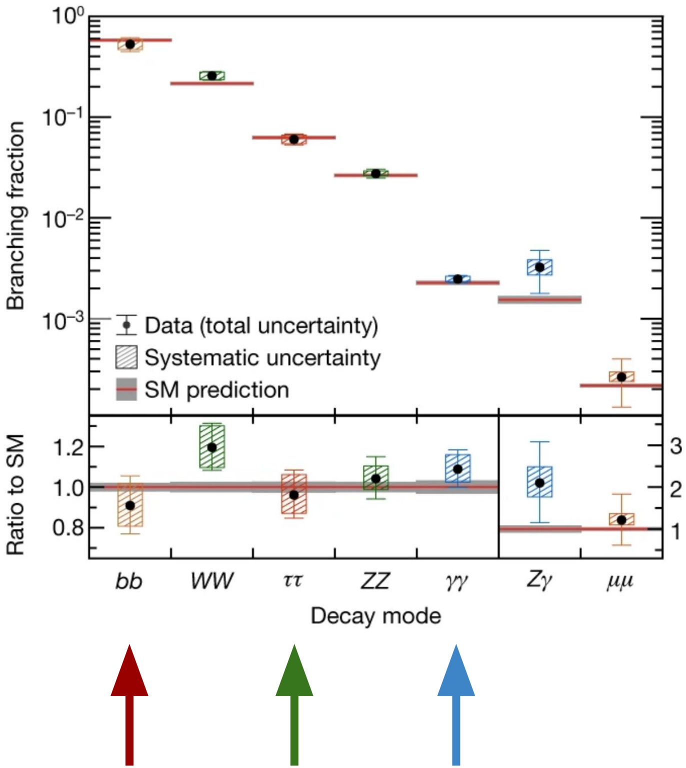
- Analyses according to Higgs-decay
- **Run 2**:
  - **$t\bar{t}H/tH \rightarrow bb$**
  - **$t\bar{t}H/tH \rightarrow \gamma\gamma$**
  - $t\bar{t}H/tH \rightarrow$ multilepton → partial Run 2 ATLAS, full Run 2 CMS

- **$t\bar{t}H/tH \rightarrow bb$:**
  - large BR, enhanced sensitivity to fermionic couplings
  - large irr. background (tt+jets) → low S/B

- **$t\bar{t}H/tH \rightarrow \gamma\gamma$:**
  - very clean signature and good S/B
  - low BR and low statistics

- $t\bar{t}H/tH \rightarrow$ multilepton:
  - good compromise
  - distinctive signatures with W, Z and τ decays
  - challenging background

Nature 607, 52 (2022)



ATLAS Run 2 $t\bar{t}H \rightarrow bb$

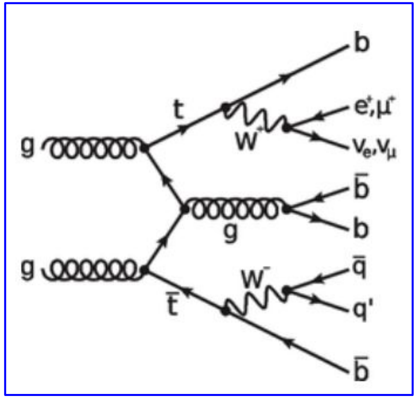
Goal:

- Measuring $t\bar{t}H(H \rightarrow b\bar{b})$ process both inclusive and in bins of Higgs p_T (STXS)
    - decay channel gives access to high-p_T kinematic regime (boosted) not so easily accessible in other channels (lack of statistics)

Strategy:

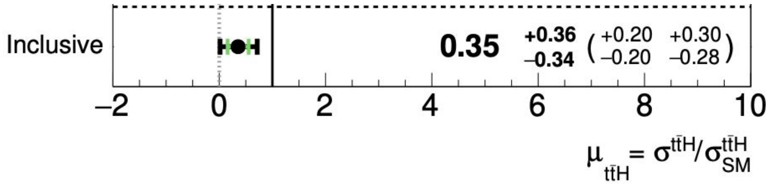
- Using lowest unprescaled single-lepton triggers for event selection
- 2 channels: based on number of leptons (τ-veto to ensure orthogonality)
    - Single lepton: Exactly one lepton ($N_\tau < 2$)
    - Dilepton: Exactly two leptons ($N_\tau = 0$)

- Main challenges related to **$t\bar{t}$+bb** background
    - difficult separation from signal
    - difficult modelling uncertainties



Previous round JHEP06 (2022) 097:

- exp. sensitivity 2.7σ
- obs. 1σ

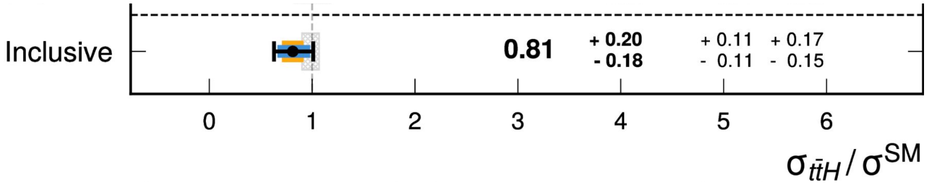


NEW!

ATLAS Legacy Run 2 $t\bar{t}H \to bb$

arXiv:2407.10904

Observed (expected) sensitivity increased to 4.6σ (5.4σ) !



Strategy:

- Sensitivity of previous measurement limited by syst. unc. in dominant $t\bar{t}$ background modelling ($t\bar{t}bb$)
  - revised treatment of different flavour components of tt+jets and new modelling for $t\bar{t}bb$
- Improve reconstruction and particle ID
  - object definition → jets p-flow and b-tagging
  - looser event selection → 8 CRs for better bkg control in data
- Improve MVA-techniques → attention-based transformer network (better Higgs reco and SR/CRs definition)
  - DNN-based H → bb tagger for SL channel (per-jet classification) → identify large-R jets coming from Higgs decays (boosted topologies)

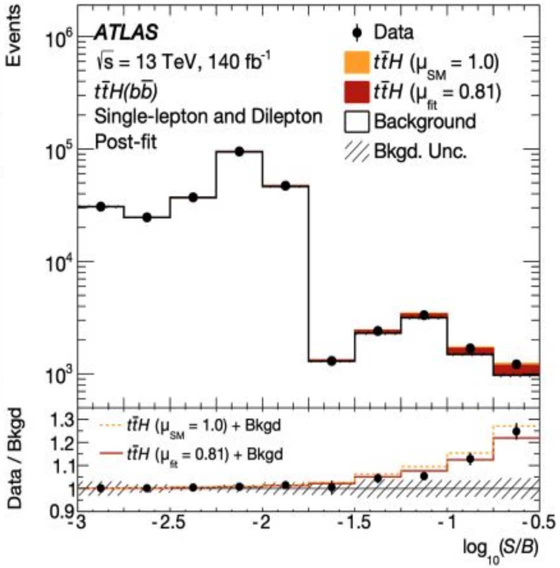
NEW!

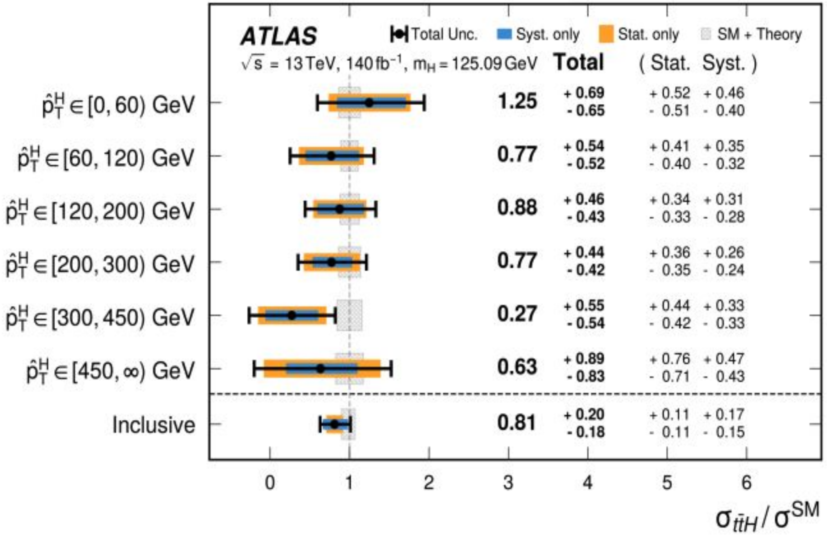
ATLAS Legacy Run 2 $t\bar{t}H \to bb$

arXiv:2407.10904

- Select 64% (29%) more single lepton (di-lepton) events → observed (expected) significance = **4.6 (5.4)σ**
- Inclusive cross-section consistent with SM

$$\sigma_{t\bar{t}H} = 411^{+54}_{-54}(stat.)^{+85}_{-75}(syst.)\text{fb}$$
$$\sigma_{t\bar{t}H,SM} = 507^{+35}_{-50}\text{fb}$$

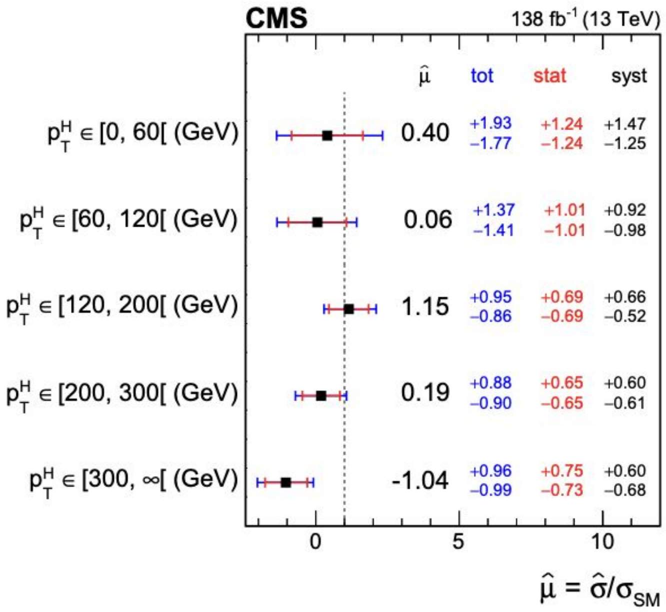


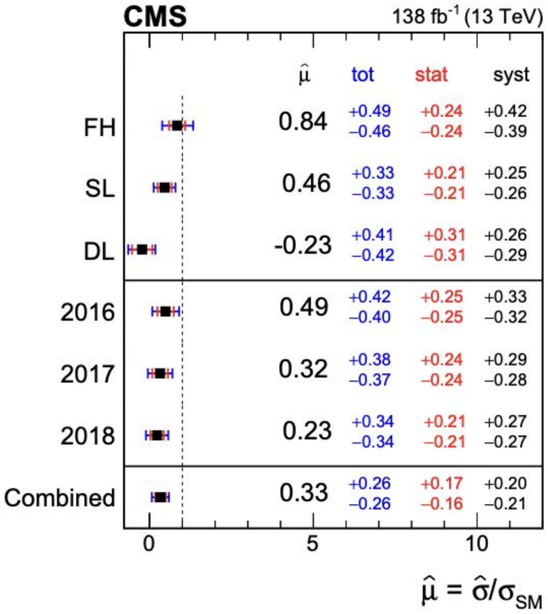


CMS Run 2 $t\bar{t}H \rightarrow bb$

NEW! arXiv:2407.10896

- Complex strategy:
  - 3 different final states of top quark decays considered (number of leptons)
  - BDT for jet-parton assignment
  - Signal extracted through DNN multi-classifiers → Simultaneous fit of discriminant scores
  - Difficult modelling of $t\bar{t}bb$ irr. background





Results:

- $t\bar{t}H$ production rate (relative to SM expectation):

0.33 ± 0.17 (stat) ± 0.21 (syst)

- An observed (expected) upper limit on the tH production rate relative to the SM expectation of 14.6 (19.3) at 95% is derived

ATLAS Run 2 $t\bar{t}H \rightarrow \gamma\gamma$

JHEP07(2023)088

Clean final-state topology: can be used to effectively distinguish it from background processes
One of the most important channels for precision measurements of Higgs boson properties

Goal:

- Measure inclusive and production mode cross-sections
- Include EFT and k-framework interpretation

Strategy:

- Select di-photon events and divide them in orthogonal categories
- Target $t\bar{t}H$/tH production via STXS → cross-section measured as a function of truth $p_T(H)$
  - from 45 to 28 STXS regions → based on targeted production, $p_T(H)$ and number of jets
- Multi-classifier BDT sensitive to particular STXS regions + additional binary BDT trained to distinguish S from B

Results presented in terms of several descriptions of Higgs boson production:

- Overall signal strength of Higgs boson production measured in the diphoton decay channel
- Separate cross-sections for the main Higgs boson production modes
- Cross-sections in 28 merged STXS regions

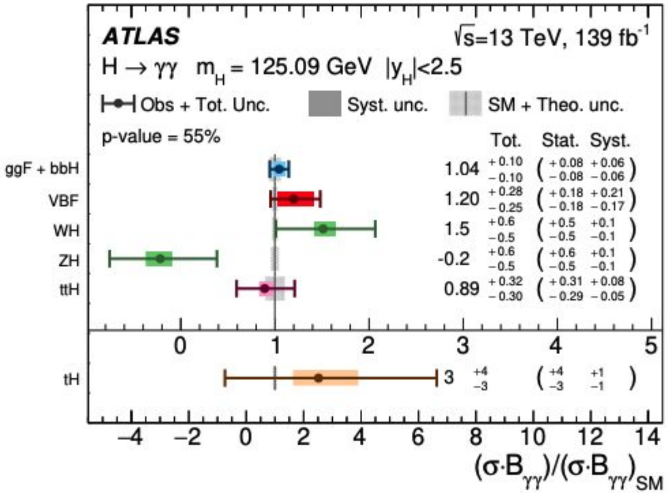
ATLAS Run 2 $t\bar{t}H \to \gamma\gamma$

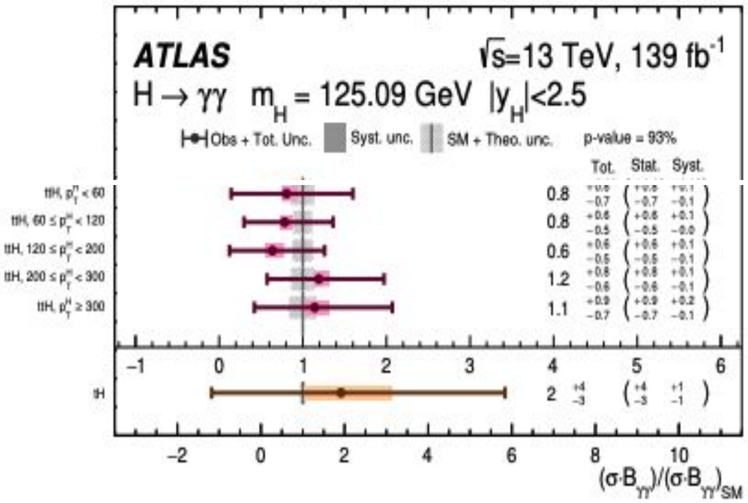
JHEP07(2023)088

- Signal extraction by a simultaneous fit to mass of the photons
- Signal strength μ treated in the LH as a single POI which scales the exp. yields in all STXS regions

$$\mu = 1.04^{+0.10}_{-0.09} = 1.04 \pm 0.06\ (\text{stat.})^{+0.06}_{-0.05}\ (\text{theory syst.})\ ^{+0.05}_{-0.04}\ (\text{exp. syst.})$$ → **good agreement with SM**

- **tH upper limit**: excludes production rate of 10 times its SM prediction or greater at 95%
- Measured STXS cross-sections are compatible with their SM predictions (*p*-value of 93%)

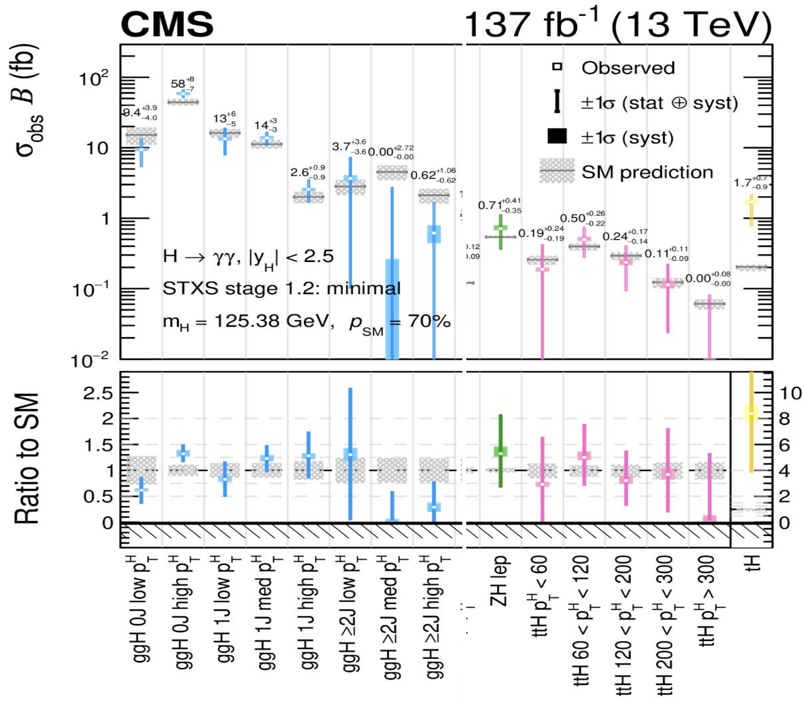




CMS Run 2 $t\bar{t}H \rightarrow \gamma\gamma$

JHEP 07 (2021) 027

- Measure range of production and coupling properties of the Higgs boson:
    - total Higgs signal strength relative to SM prediction measured to be 1.12 ± 0.09
    - simultaneous measurement of signal strengths of the 4 main Higgs production mechanisms → compatible with SM prediction
    - Two measurements performed within STXS:
        - 17 and 27 independent kinematic regions measured simultaneously with p-values with respect to the SM of 31% and 70%
        - simultaneous measurement of ttH production in 5 different regions of p_tH measured for first time
- **tH upper limit**: excludes production rate of 14 times its SM prediction or greater at 95%

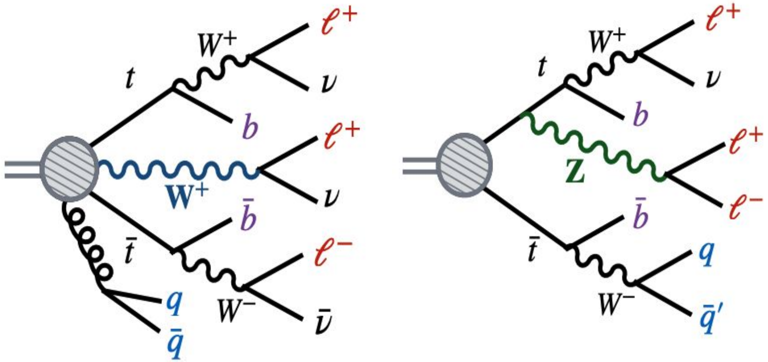


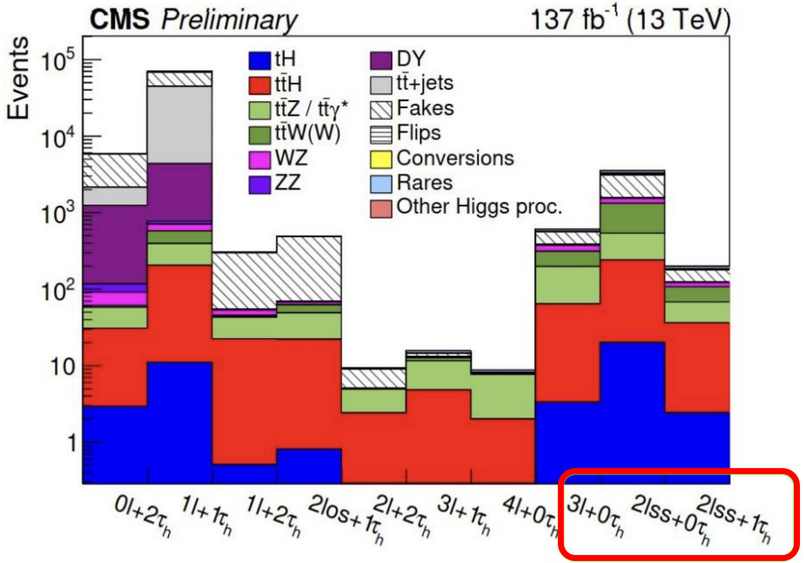
- All other results (couplings) also in agreement with the SM expectations.

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

CMS Run 2 $t\bar{t}H \rightarrow$ multilepton

- Analysis targeting $H \rightarrow WW/ZZ/\tau\tau$ decay channels
- Multitude of final states including e/μ leptons and τ_{had}





- Challenging background
  - irreducible: ttW, ttZ/gamma, diboson
  - reducible: non-prompt or fake leptons

- **Dedicated categories sensitive to tH production**

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

CMS Run 2 tt̄H → multilepton

- 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 bkg
- Simultaneous fit of signal and control regions

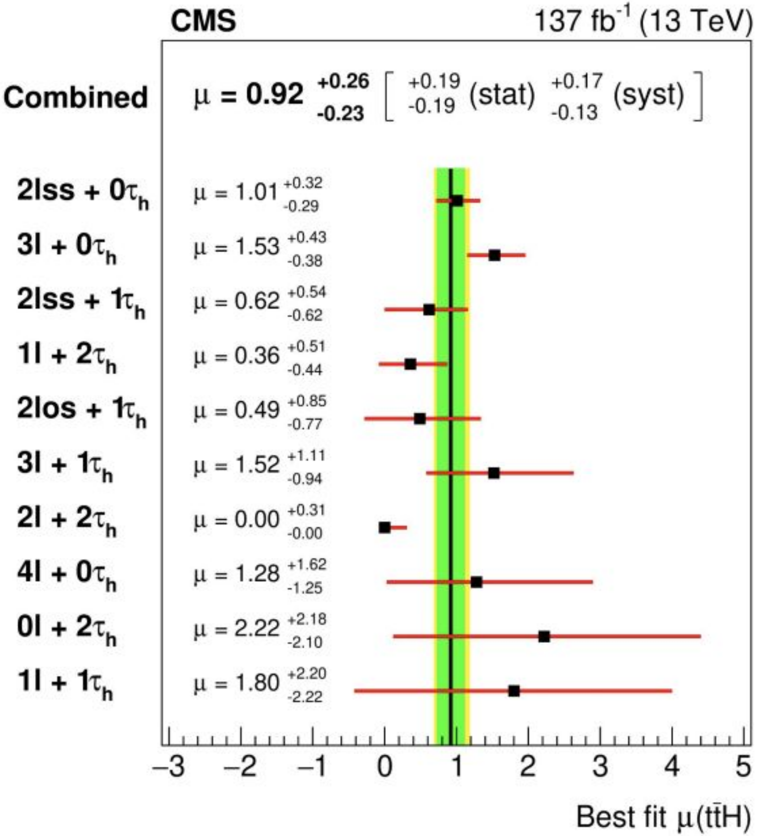
- Measured production rates corresponding to (respective SM expectations):

ttH and tH signal strength

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

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

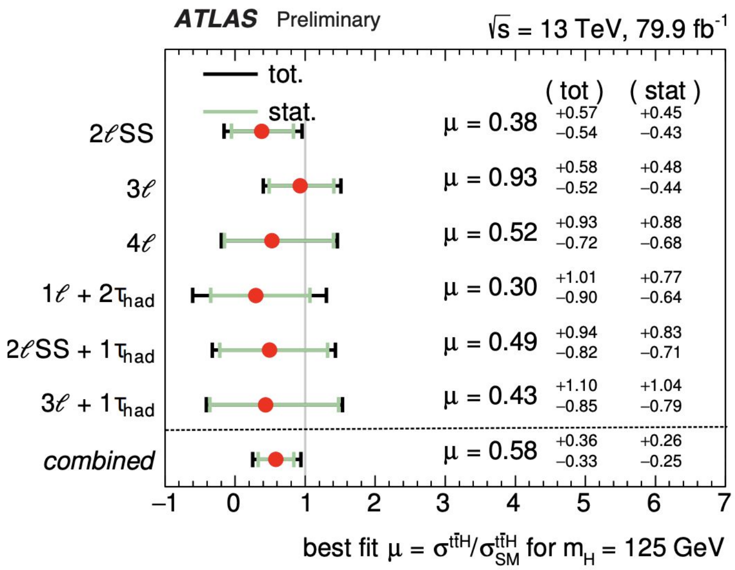
- Corresponding observed significance:
  ttH: 4.7σ (5.2σ exp.), tH: 1.4σ (0.3σ exp.)



ATLAS-CONF-2019-045

ATLAS Run 2 $t\bar{t}H \rightarrow$ multilepton

- Partial Run 2 (80 fb^{-1} only)
- 6 final states targeting Higgs decays to WW^* , $\tau\tau$, and ZZ^*
- Categorised by the number and flavour of charged-lepton candidates



Results:

- Excess of events over the expected background from SM processes found → observed significance of 1.8 standard deviations (expected 3.1 for SM Higgs)
- Best-fit result of observed ttH production cross-section (in agreement with the SM prediction 507^{+35}_{-50} fb):

$$\hat{\sigma}(t\bar{t}H) = 294^{+132}_{-127}\ (\text{stat.})^{+94}_{-74}\ (\text{exp.})^{+73}_{-56}\ (\text{bkg. th.})^{+41}_{-39}\ (\text{sig. th.})\ \text{fb} = 294^{+182}_{-162}\ \text{fb}$$

- Modelling issues observed in regions dominated by $t\bar{t}W$ production
- Needed improved description of the $t\bar{t}W$ background for greater precision in the future → $t\bar{t}W$ diff. meas.

CP STUDIES

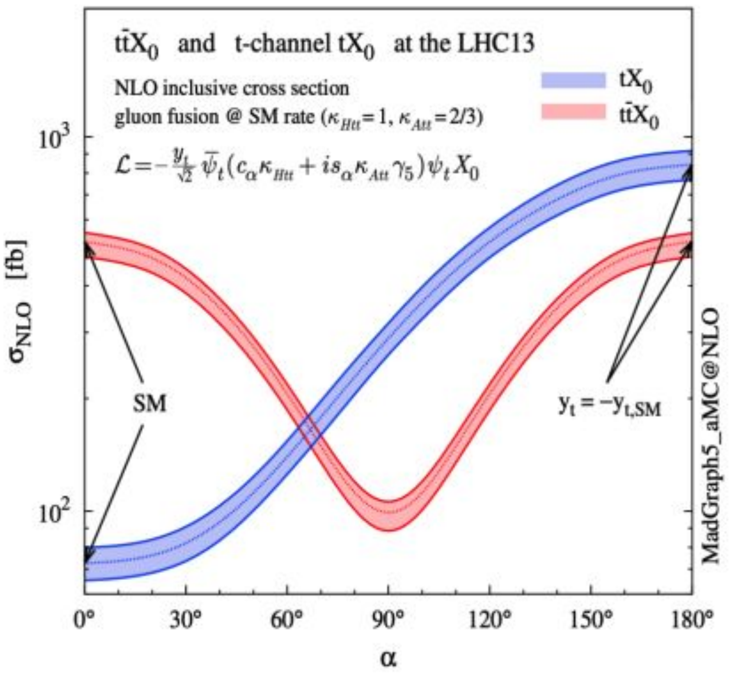
Why CP studies?

- SM Higgs is a CP-even scalar → no CP violation
- BSM: CP violation in Higgs interactions → evidence for new physics

- CP violation needed to explain baryon asymmetry of the universe
  - CKM and PMNS matrices insufficient to account for cosmic asymmetry

- Additional CP violating sources will be unequivocal signs of physics beyond the standard model

- CP-odd only couplings strongly excluded by ATLAS and CMS, while CP-even/odd mixing NOT
- Mixing typically modelled with a mixing angle between CP-even and CP-odd couplings



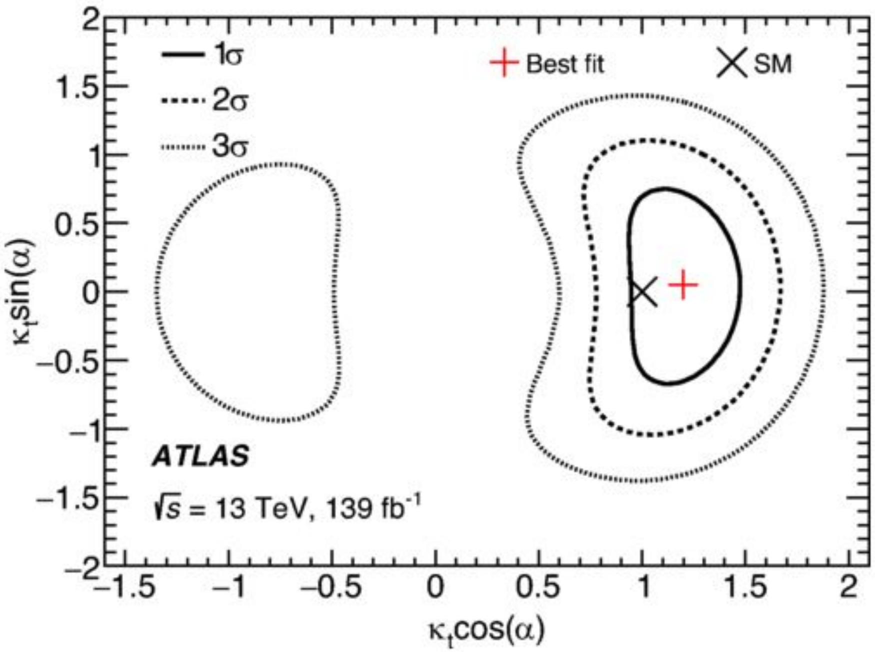
Eur. Phys. J. C 75 (2015) 6, 267 arXiv:1504.00611 [hep-ex]

ttH/tH → $\gamma\gamma$ CP studies ATLAS

- Photons are CP-even → provide a clean way to probe CP nature of Higgs boson
- Look for angular distributions of the photons and other variables that could indicate a CP-odd component

Phys. Rev. Lett. 125 (2020) 061802

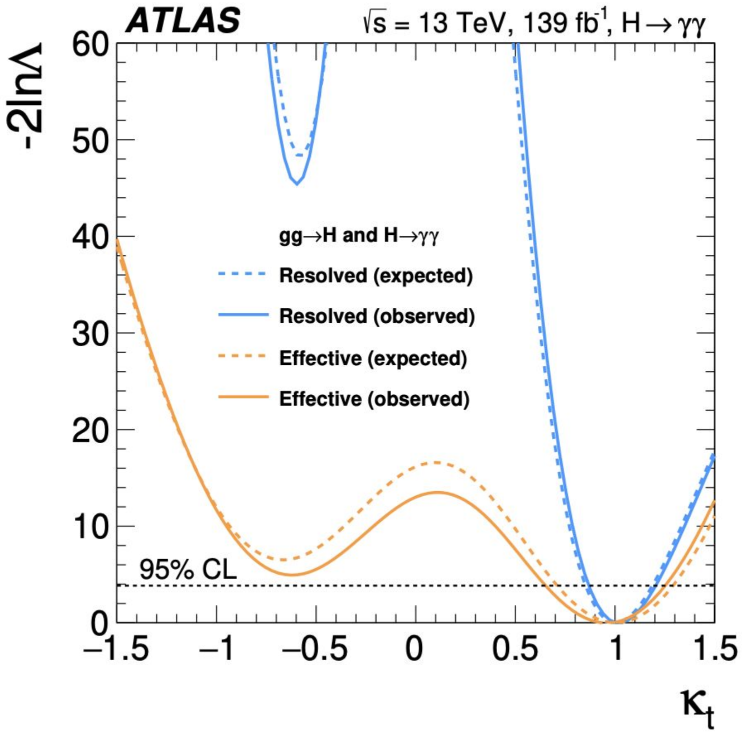
- 2 channels: Leptonic or Hadronic based on top decay
- Event categorization in two steps:
  - BDT to separate $t\bar{t}$H/non-resonant bkg
  - BDT to separate CP-even/CP-odd couplings
- Simultaneous fit to m($\gamma\gamma$) across all categories
- Strongly support CP even hypothesis:
  - **pure CP-odd (α=90) excluded with 3.9σ** and **|α|>43 excluded at 95% CL**



ttH/tH → $\gamma\gamma$ CP studies ATLAS

JHEP07(2023)088

- Results interpreted in models of Higgs coupling modifiers
  - all couplings compatible to SM values
- In figure (neg log LH scans):
  - $H \rightarrow \gamma\gamma$ and $gg \rightarrow H$ either parametrised as a func. of κ_t (blue) or fixed to SM expectation (orange)
- Sensitivity to sign of κt thanks to tH categories
  - **good agreement with SM κ_t=1 and κ_t < 0 excluded at 2.2σ**



ttH/tH → bb CP studies ATLAS

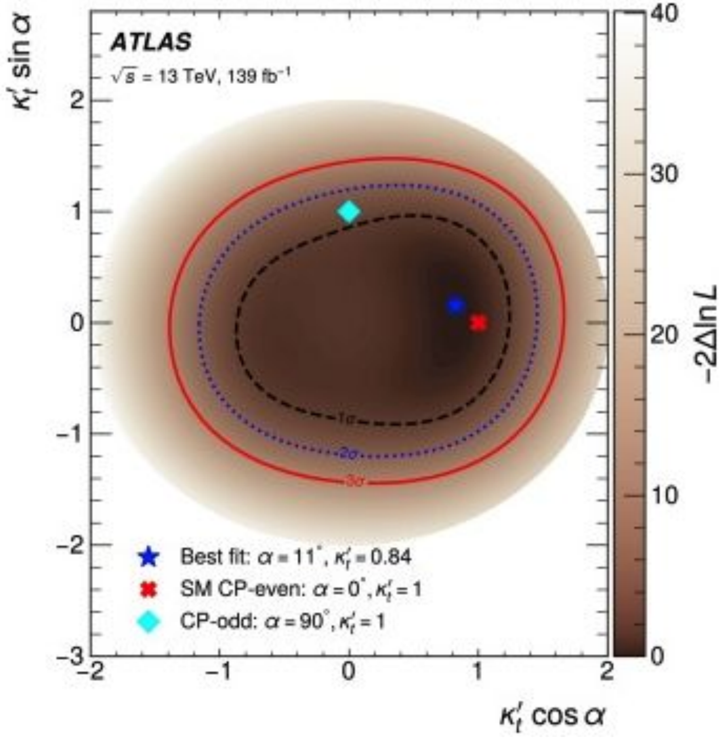
PLB 849 (2024) 138469

- Events containing one or two e or μ used
- MVA techniques used to select regions enriched in ttH and tH events where dedicated *CP*-sensitive observables are exploited (relying on angular separations between reconstructed top quarks or lepton candidates)

- Best-fit values and the exclusion contours in α and κ_t'
  - best-fit value for the *CP* mixing angle α is 11°−73°+52° and overall coupling strength κ_t' is 0.84−0.46+0.30

→ in agreement with SM expectations of α=0◦ and κ_t'=1

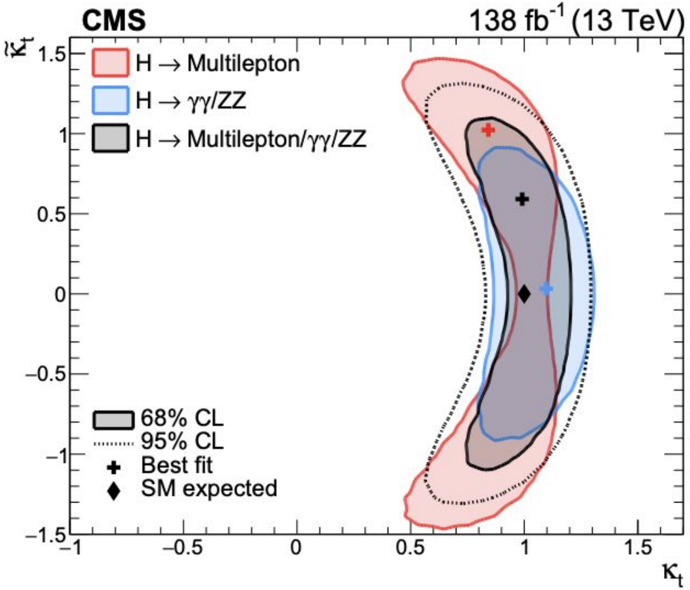
- Observed value of CP mixing angle:
  - exclude pure CP-odd scenario (α = 90°) at 1.2σ level



ttH/tH (H→WW or H→$\tau\tau$) CP studies CMS

JHEP 07 (2023) 092

- Study targets H→ WW or H→ $\tau\tau$ with t→ Wb: final states with at least two leptons are studied
- ML techniques to enhance the separation of CP-even from CP-odd scenarios (final states with at least 2 leptons)
- 2-dim confidence regions set on κ_t and $\tilde{\kappa}_t$
- No significant fractional CP-odd contributions observed parametrised by **$|f^{Htt}_{CP}|$**
- $|f^{Htt}_{CP}|$ = 0.59 with an interval of (0.24, 0.81) at 68% CL
- Combined results with previous H→ ZZ and H→γγ yielding two- and one-dimensional confidence regions constraining κ_t and $\tilde{\kappa}_t$ to be within (0.86, 1.26) and (−1.07, 1.07) at 95% CL
- Agreement with SM CP-even prediction ($|f_{HttCP}|$=0)



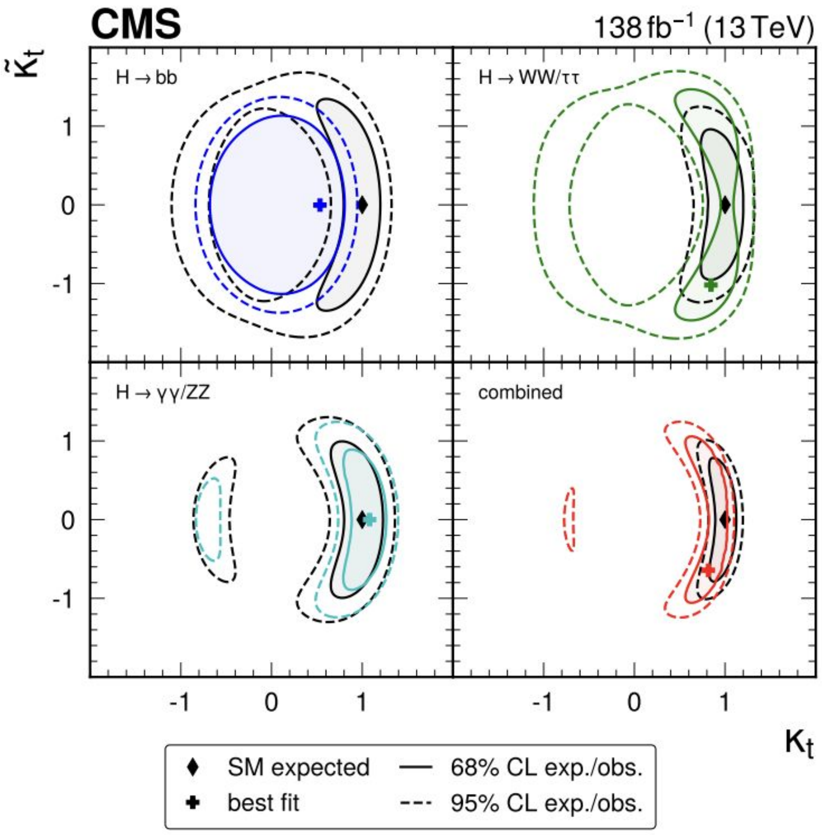
$$f^{Htt}_{CP} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} \text{sign}(\tilde{\kappa}_t/\kappa_t)$$

ttH/tH (H→ bb) CP studies CMS

arXiv:2407.10896

Results of combination:

- Values of the LH ratio test statistic as a function of κ_t and $\tilde{\kappa}_t$ for the individual channels and their combination → **yields best fit values of (κ_t , $\tilde{\kappa}_t$) of (0.82, −0.65)**.
- Change of sign of $\tilde{\kappa}_t$ in H → WW and H →$\tau\tau$ channels not meaningful but reflects the degeneracy of the likelihood with respect to $\tilde{\kappa}_t$
- Sensitivity of combined result driven by non-bb channels
  - H → bb channel leads to slight improvement in sensitivity, visible in the reduction of the 68% and 95% CL confidence regions



Summary & conclusions

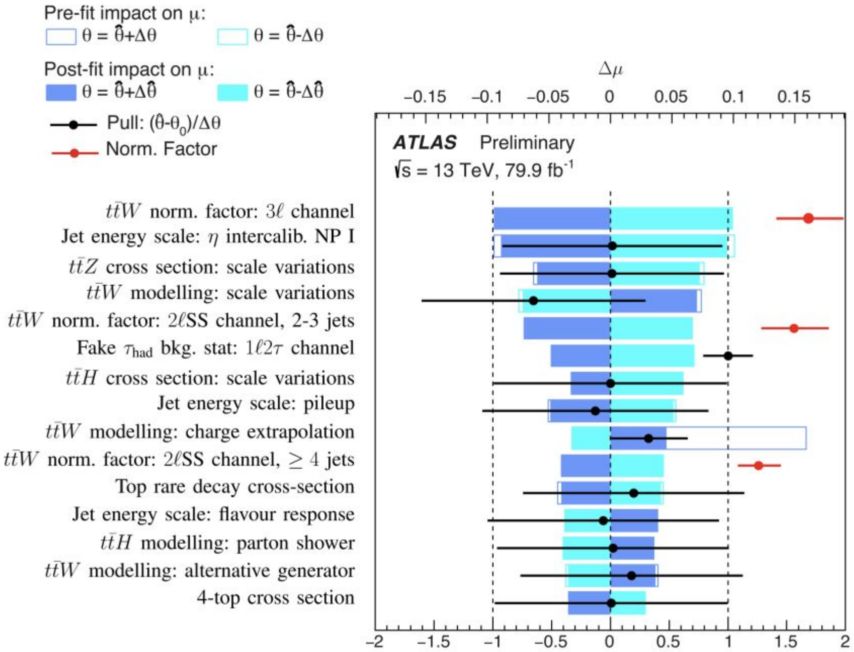
- **Why $t\bar{t}H/tH$?**
  - top-Higgs Yukawa coupling direct measurement
  - sensitive to BSM
- **ATLAS measurements**
  - **$t\bar{t}H \rightarrow bb$**: great improvement wrt previous round → observed (expected) significance = **4.6σ (5.4σ)**
  - **$t\bar{t}H \rightarrow \gamma\gamma$**:
    - **tH upper limit**: excludes production rate of 10 times its SM prediction or greater at 95%
    - sensitivity κ_t sign thanks to tH categories → **agreement with SM and $\kappa_t < 0$ excluded at 2.2σ**
  - **$t\bar{t}H \rightarrow$ multilepton**: partial Run 2 dataset only, modelling issues in $t\bar{t}W$ dominated regions
- **CMS measurements**
  - **$t\bar{t}H \rightarrow bb$**: **observed (expected)** upper limit on the **tH** production cross section relative to the SM expectation of **14.6 (19.3)** at 95%
  - **$t\bar{t}H \rightarrow \gamma\gamma$**: excludes production rate of 14 times its SM prediction or greater at 95%
  - **$t\bar{t}H \rightarrow$ multilepton**: **ttH: 4.7σ (5.2σ exp.), tH: 1.4σ (0.3σ exp.)**
- **CP interpretation**
  - no evidence for a CP-odd component in Higgs boson interactions

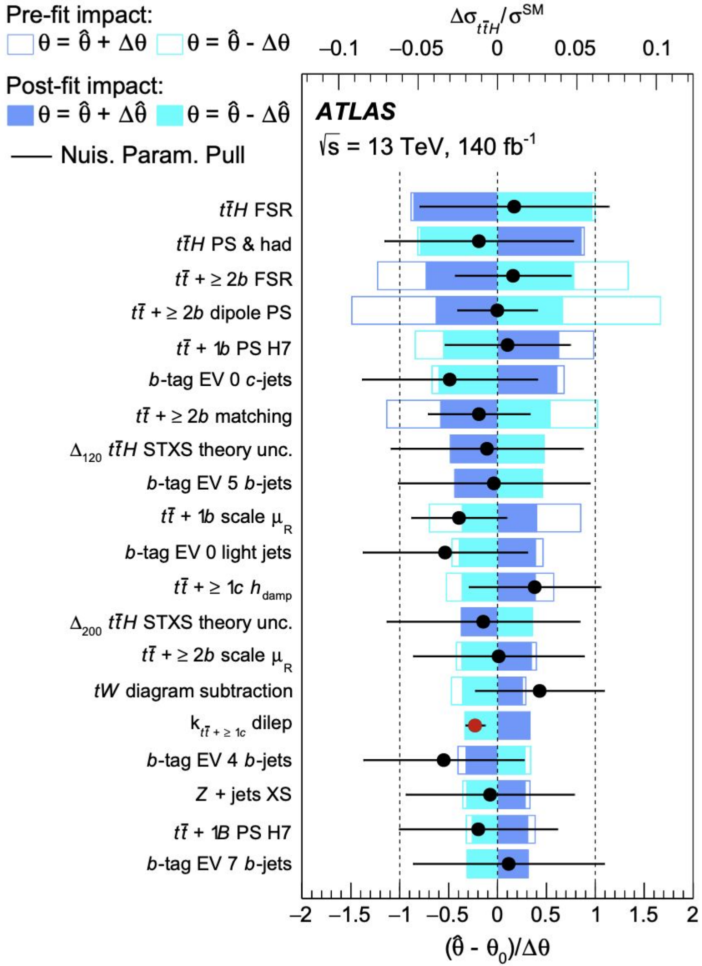
THANKS!

- Grants PID2021-124912NB-I00 and PID2021-125069OB-100 funded by MCIN/AEI/ 10.13039/501100011033 and by “ERDF A way of making Europe”
- Project ASFAE/2022/010 funded by MCIN, by the European Union NextGenerationEU (PRTR-C17.I01) and Generalitat Valenciana

BACKUP

ATLAS ttH-ML and H→ bb ranking plots

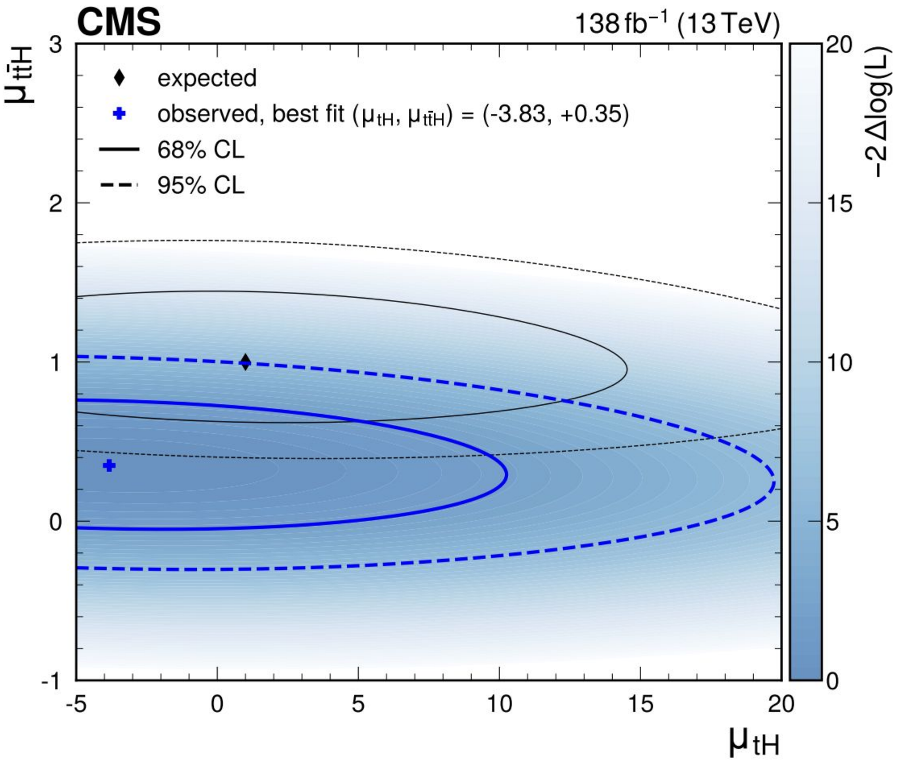




CMS ttH/tH (H→ bb)

CMS PAS HIG-19-011

- Simultaneous fit of the ttH and tH signal strength modifiers:
  - observed and expected values of the LH-ratio test statistic with best fit values of **μ_{tH}, μ_{ttH} = −3.83, 0.35**
  - correlation between the ttH and tH signal strength modifiers moderate → demonstrates the discrimination between the two signal processes achieved in this analysis



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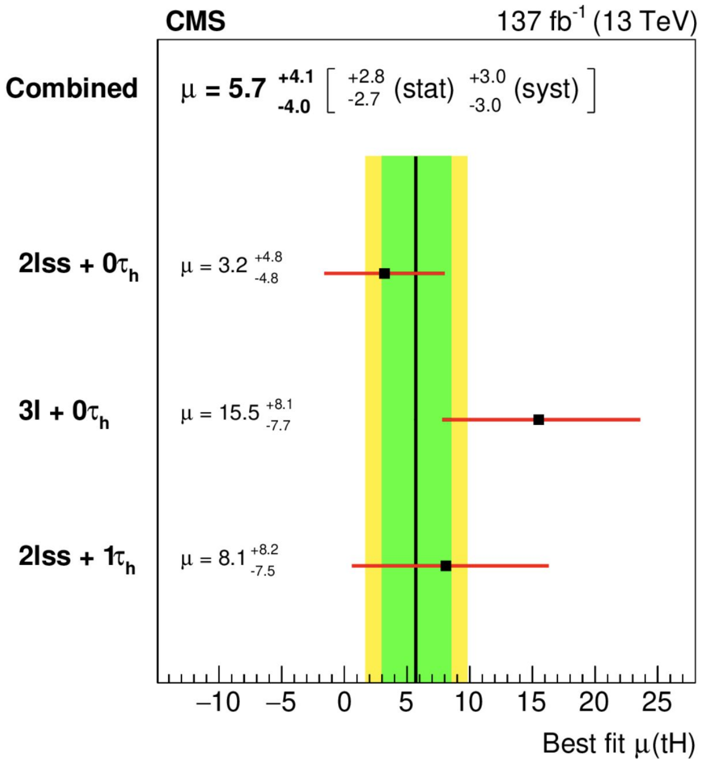
CMS ttH/tH (H→ multilepton)



CP interpretation

- Measurements in fermionic couplings:
  - CP-odd mixing may occur in Yukawa couplings at tree level, most notably with heavier third generation fermions (taus and top quarks), and can be introduced via an effective term
- Typically modelled with a mixing angle between CP-even and CP-odd couplings

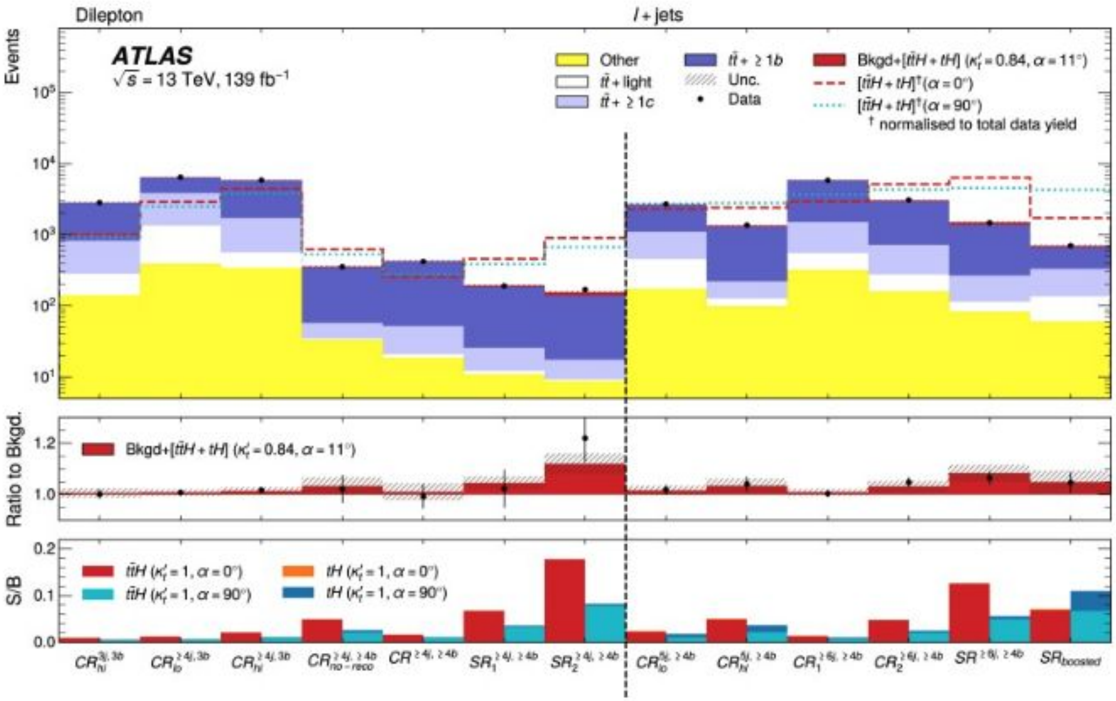
$$\mathcal{L} = -\kappa_t \bar{\psi} e^{i\alpha\gamma^5} \psi h$$
$$= -\kappa_t \bar{\psi}(\cos\alpha + i\gamma^5 \sin\alpha)\psi h$$
$$= \underbrace{-\kappa_t \cos\alpha \bar{\psi}\psi h}_{\text{CP-even part}} - \underbrace{i\kappa_t \sin\alpha \bar{\psi}\gamma^5 \psi h}_{\text{CP-odd part}}$$

Choice of α, κ_t affects the cross section and the kinematical properties of processes

ttH/tH → bb CP studies ATLAS

[PLB 849 (2024) 138469]

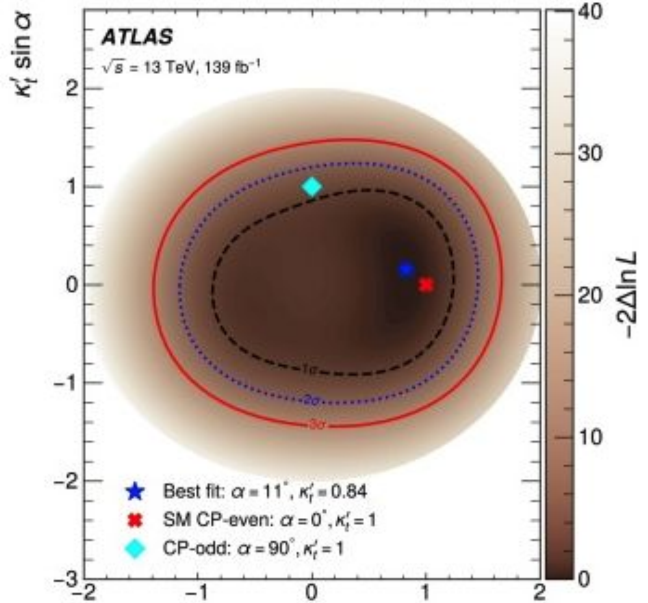
- Analysis split into ℓ+jets and dilepton categories
  - Further division according to number of jets, b-jets, and boosted signatures



- BDTs trained for various purposes:
  - Reconstruction: assigns jets from Higgs or top quark decays
  - Classification: separates ttH from background
- CP sensitive observables:
  - p1/2 = top quark momenta, pz = beam axis
  - Assumes knowledge of neutrino 4-momenta to reconstruct p1/2 → z-component obtained using neutrino weighting

CP studies ATLAS

$ttH/tH \rightarrow bb$



$ttH/tH \rightarrow \gamma\gamma$