Study of CP properties of top-Higgs interaction in ttH/tH, H→γγ channel with ATLAS experiment

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Higgs potential and BSM opportunity

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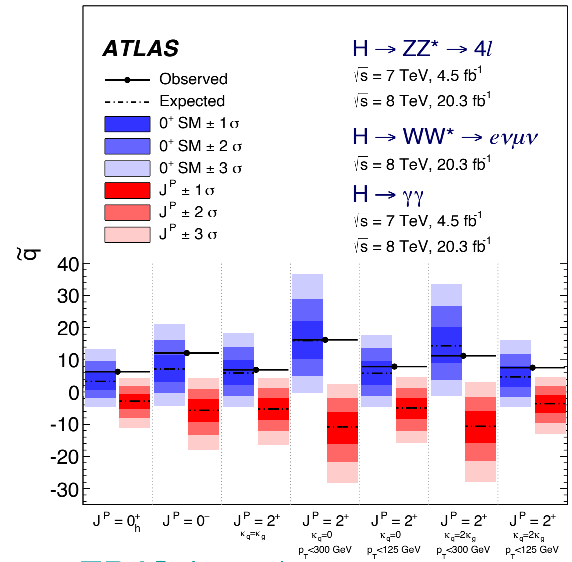
Introduction

- Large matter-antimatter asymmetry in Universe cannot be explained by known CP violation mechanism in SM: **looking for additional CP violation sources is well-motivated**
- Study of CP properties in Higgs sector started with **V-H** interactions since the Higgs boson discovery in 2012
- CP properties of fermion Yukawa coupling, in particular the largest **top Yukawa coupling**, were not **directly studied** until Run 2



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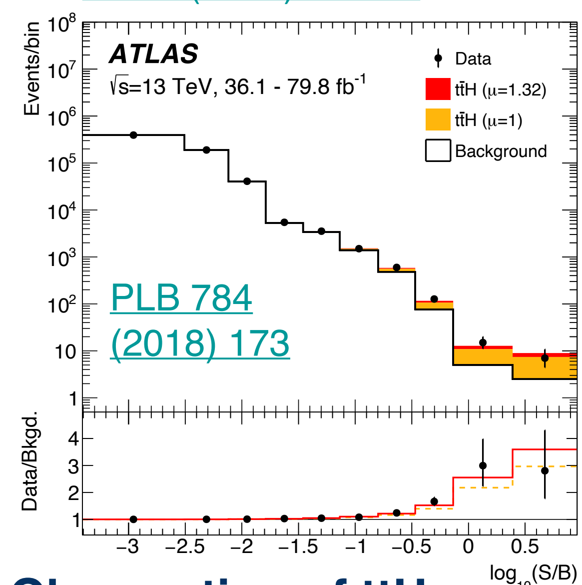


PLB 784 (2018) 173

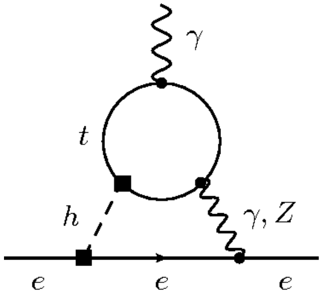
Observation of ttH

CP properties of top Yukawa coupling

- The Lagrangian for t-H interaction including CP mixing is

$$\mathscr{L}_t = -\frac{m}{v}\kappa_t(\cos(\alpha)\bar{t}t + i\sin(\alpha)\bar{t}\gamma_5 t)H,\ \kappa_t > 0,\ \alpha \in [-\pi, \pi]$$

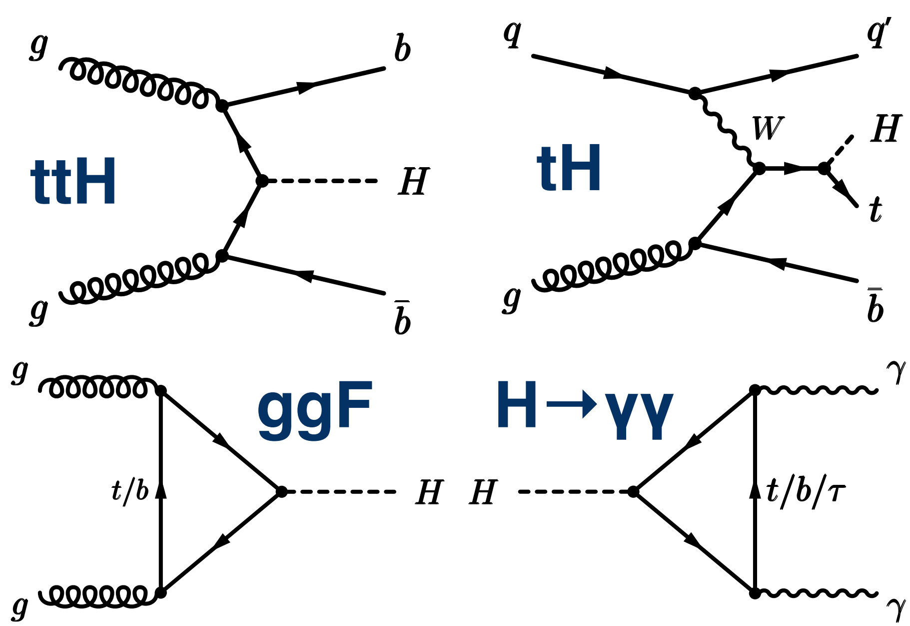
SM corresponds to **α = 0, κ_t = 1**, full CP odd is **α = 90°**

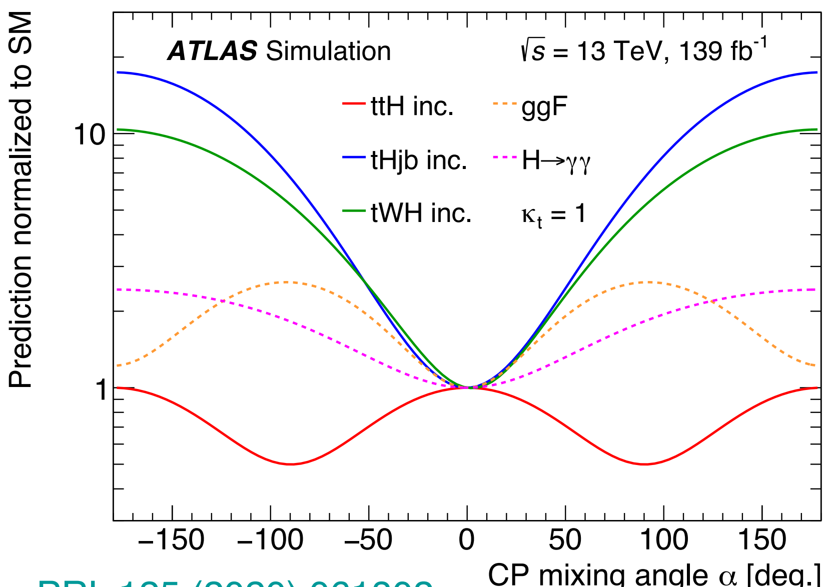


- Only **indirect** constraints on CP mixing in **t-H** interaction existed before ttH observation
  - Stringent limits from **EDMs (e, n, …)**: $\kappa_t \sin(\alpha) < 10^{-3}$
  - Also from loop-induced **H→γγ** and **ggF** rates: $\kappa_t \sin(\alpha) < \sim 0.5$
- **The ttH/tH production mode** opens a new possibility to **probe CP mixing** **directly in the top Yukawa coupling at tree-level**
- **The H→γγ channel** is ideal for this study due to excellent sensitivity and clean signature

What if there is CP mixing?

- The presence of a CP odd component in t-H coupling alters:
  - Cross sections as well as kinematics of **ttH & tH processes**: provide **direct constraint** of CP mixing in top Yukawa coupling (focus of this analysis)
  - H→γγ BR and ggF cross-sections: indirect constraint, also sensitive to other new physics scenarios

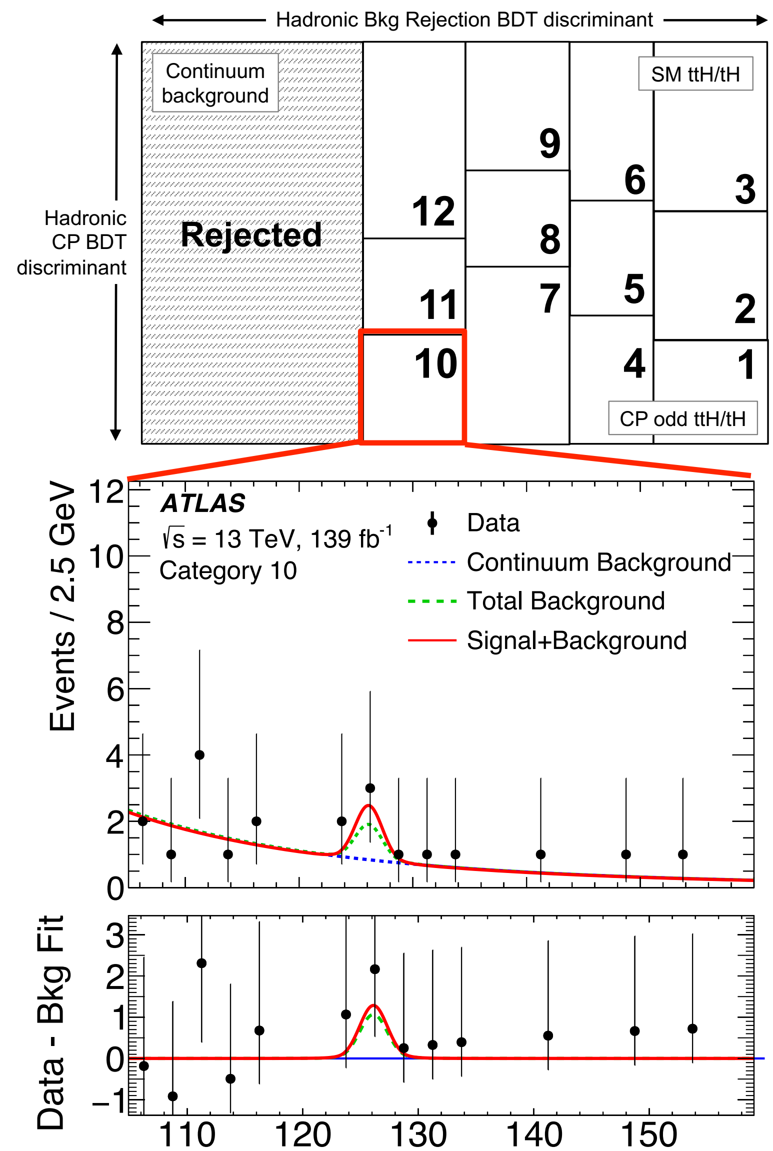




PRL 125 (2020) 061802

Analysis strategy

- Divide diphoton sample into two regions
  - **Hadronic** (**≥3 jets, ≥1 b-jet, 0 lep**)
  - **Leptonic** (**≥1 b-jet, ≥1 lep**)
- In each region, train following two BDTs (using XGBoost package)
  - **Bkg. rejection BDT**: separate ttH-like events from continuum background
  - **CP BDT**: separate CP-even ttH/tH events from CP-odd
- Divide categories on 2D plane of bkg. rejection vs. CP BDTs
- Fit the $m_{\gamma\gamma}$ spectrum in all categories simultaneously to extract signal



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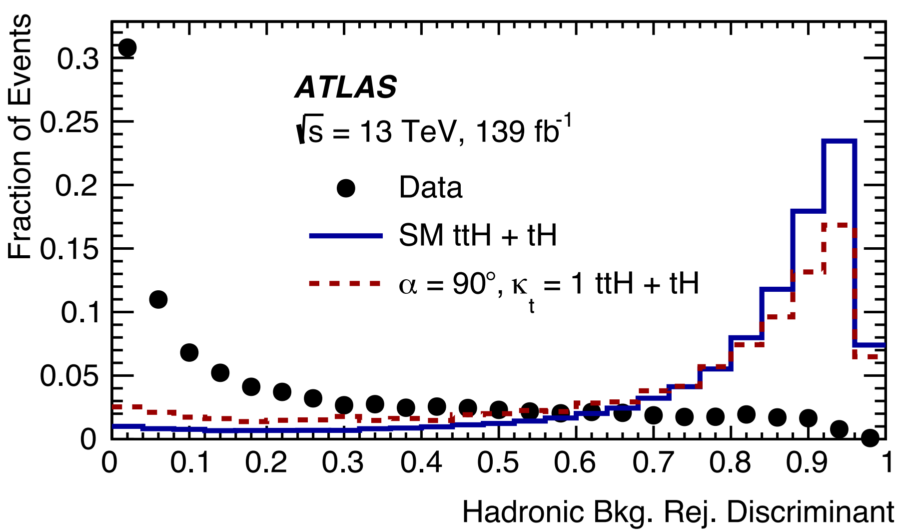
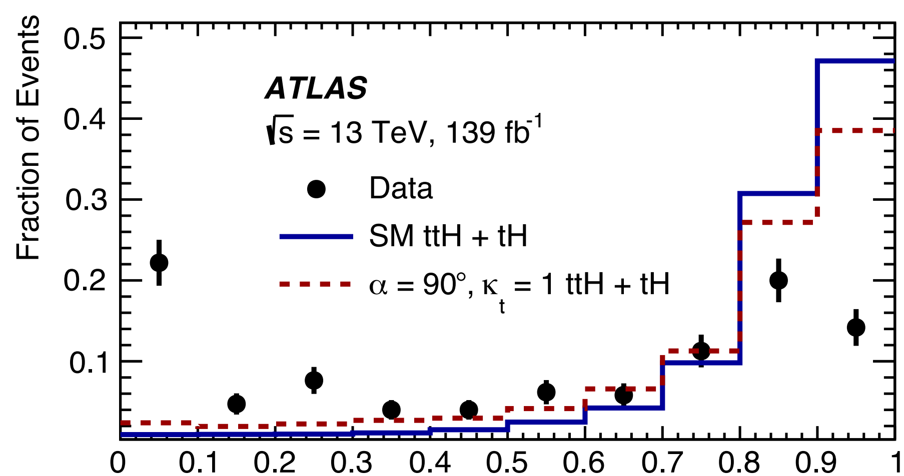
Background rejection BDT

- Use the same BDT discriminant (but not categories!) from ttH search, which is trained using **low-level inputs** such as 4-vec. of γ, j, l, and MET
- Serves the purpose of CP analysis very well
  - Good rejection of background; good acceptance of ttH/tH signal
  - Weak dependence on CP mixing angle





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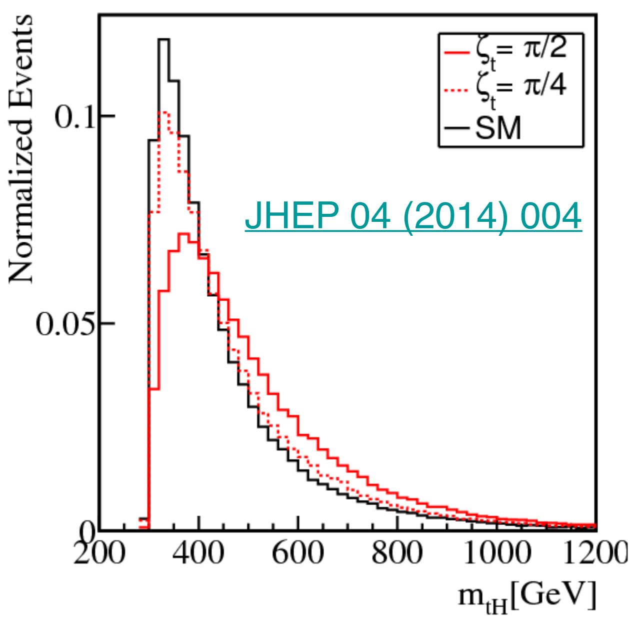
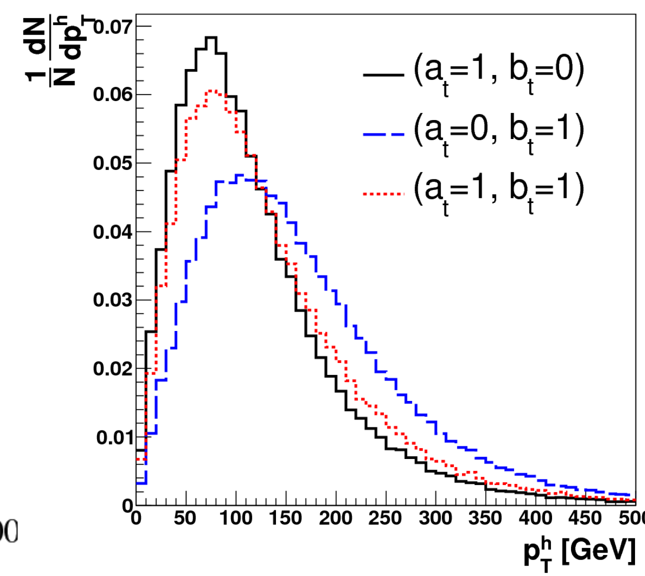
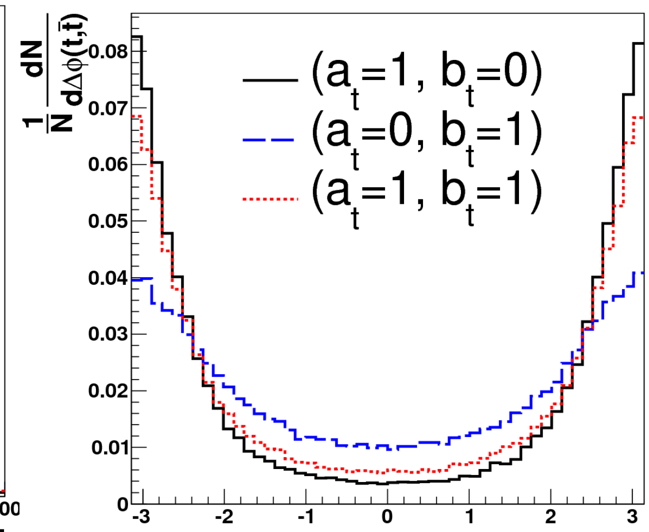
CP sensitive observables

- Compared with SM (CP even), CP odd ttH/tH gives
  - Larger m_{tH} and $m_{t\bar{t}}$; more boosted $p_T(H)$
  - Less back-to-back $\phi(t\bar{t})$; larger opening $\eta(t\bar{t})$
- Exploit shape information in this analysis. Avoid relying on normalization dependence



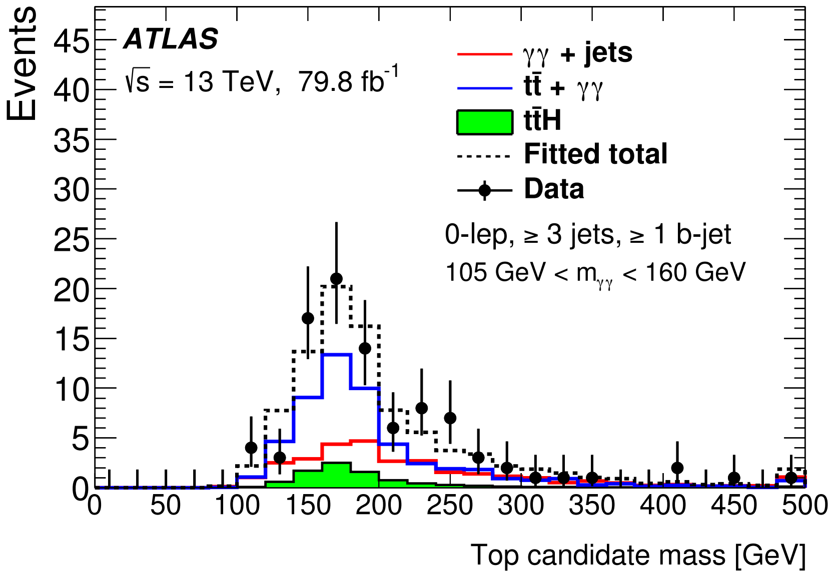
JHEP 04 (2014) 004

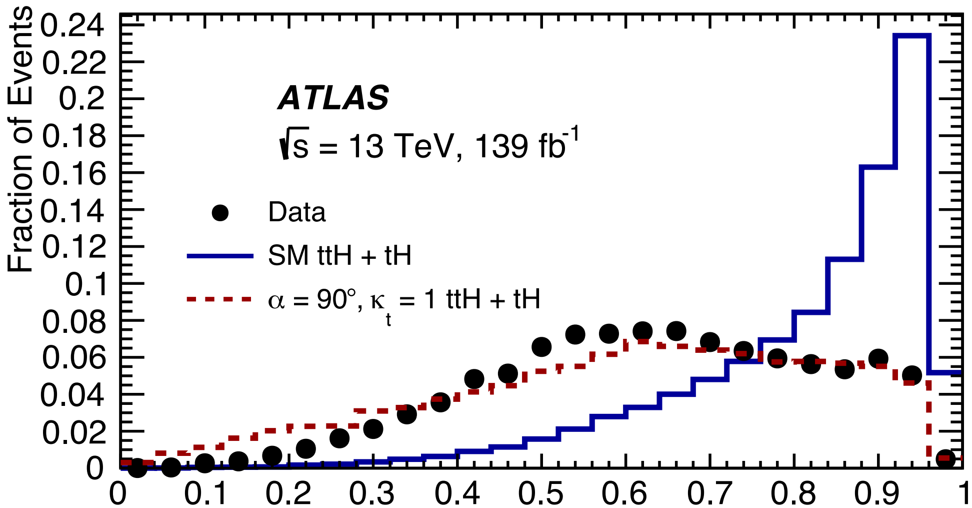




PRD 92, 015019 (2015)

CP BDT





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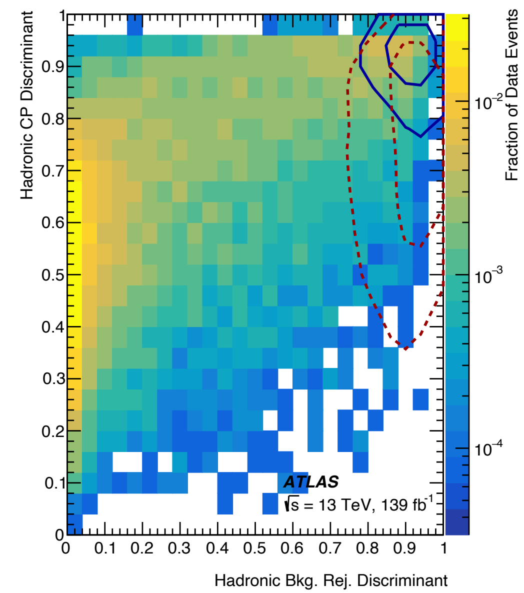
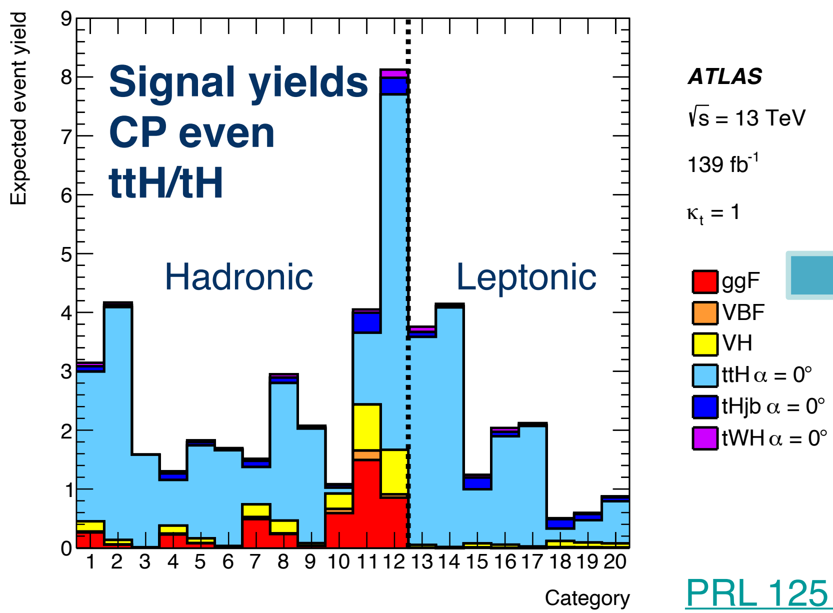
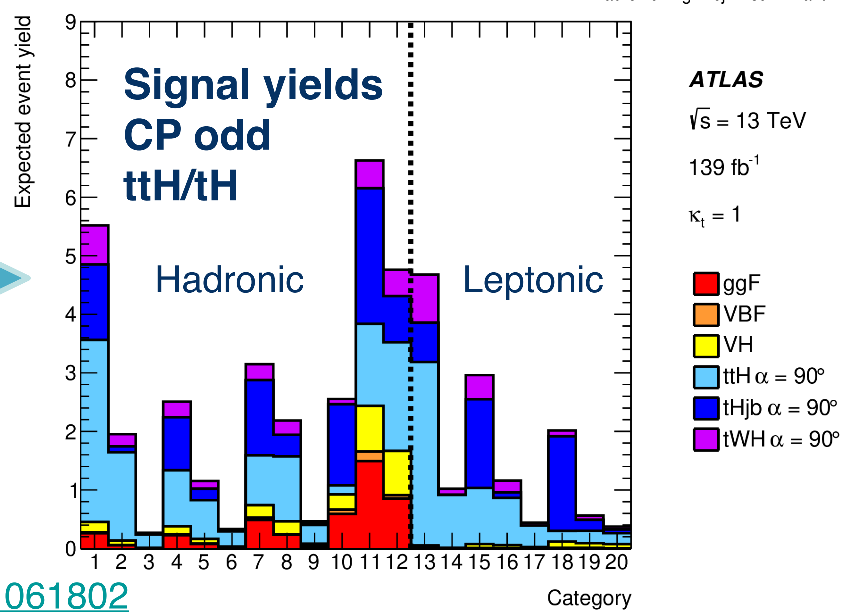
- Train **top reconstruction BDT** to reconstruct two top quarks t_1, t_2
  - Trained using ttH sample: correct pairing vs. wrong paring
  - In case t_2 cannot be built, sum up all remaining objects as t_2
- Train **CP BDT** to separate between **CP even** and **CP odd** ttH+tH
  - p_T / η of diphoton system; H_T, n_{jets}, n_{bjets}, $\Delta R(\gamma, j)$
  - p_T / η / ϕ / **top reco. BDT** score of t_1 and t_2, $m_{t_1 H}$, $m_{t_1 t_2}$, $\phi(t_1 t_2)$, $\eta(t_1 t_2)$

Categorization

- Scan category boundaries on 2D bkg. rejection BDT vs. CP BDT plane to optimize both SM ttH significance and CP separation
- **20 analysis categories** defined in total
  - 12 categories in hadronic region, 8 in leptonic







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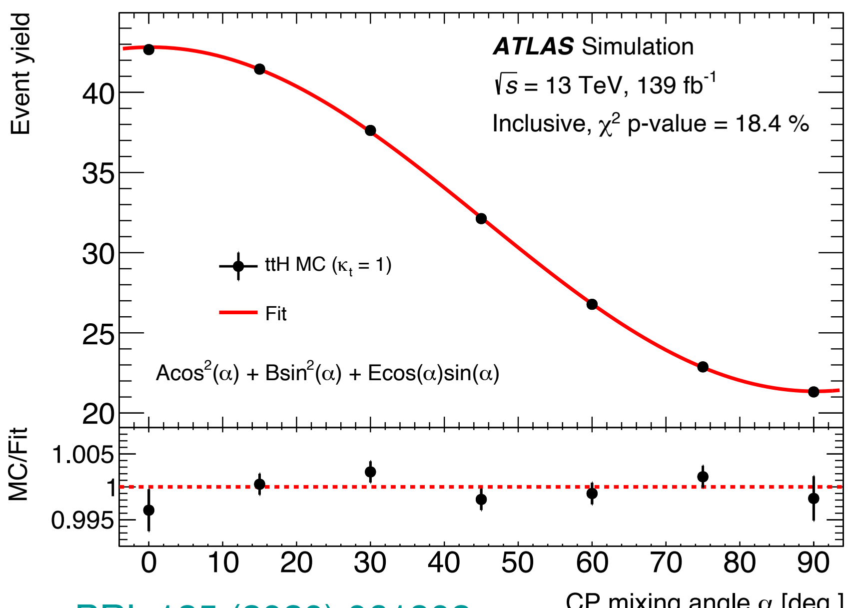
ttH signal yield parameterization

- Parameterize **ttH** and **tH** signal yields in each category as **mixing angle** α and **top Yukawa coupling strength** κ_t
- For ttH process, use

$$A\kappa_t^2\cos^2(\alpha) + B\kappa_t^2\sin^2(\alpha) + E\kappa_t^2\sin(\alpha)\cos(\alpha)$$



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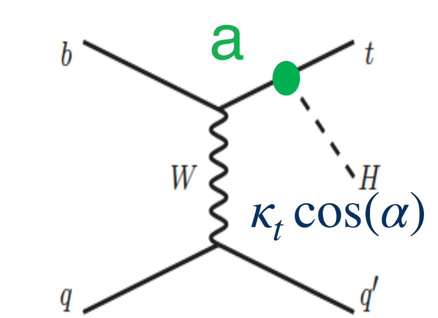
- Parameterization describe MC predictions well in all categories
- Coefficient E for interference term found to be negligible as expected

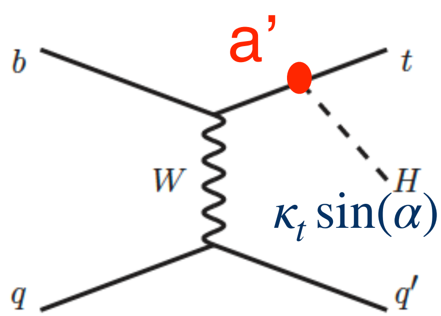
tH signal yield parameterization

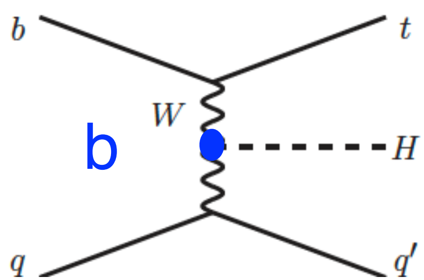
- For tHW and tHjb processes, need to use more complicated parameterizations considering interference between t-H and W-H

$$A\kappa_t^2\cos^2(\alpha) + B\kappa_t^2\sin^2(\alpha) + C\kappa_t\cos(\alpha) + D\kappa_t\sin(\alpha) + E\kappa_t^2\sin(\alpha)\cos(\alpha) + F$$

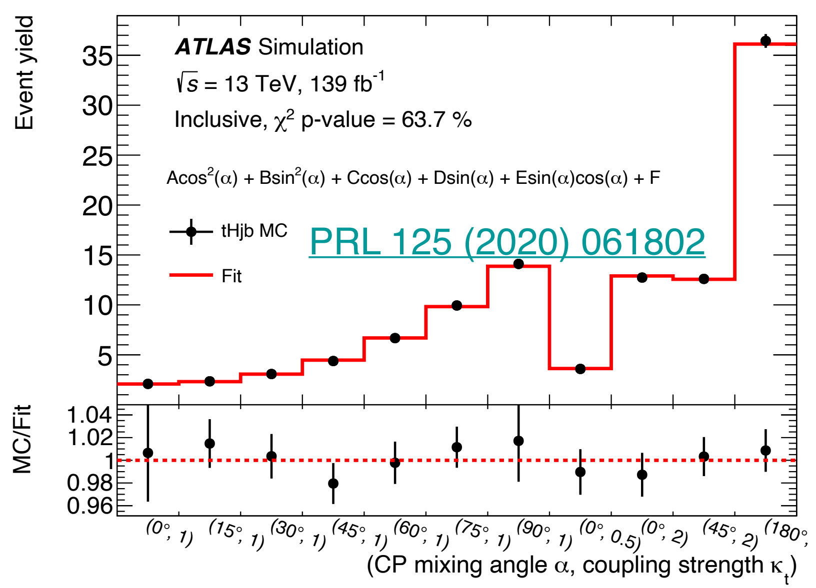
a² | a'² | 2 Re(a b) | 2 Re(a' b) | 2Re(a a') | b²







Interference terms between CP even and odd found negligible

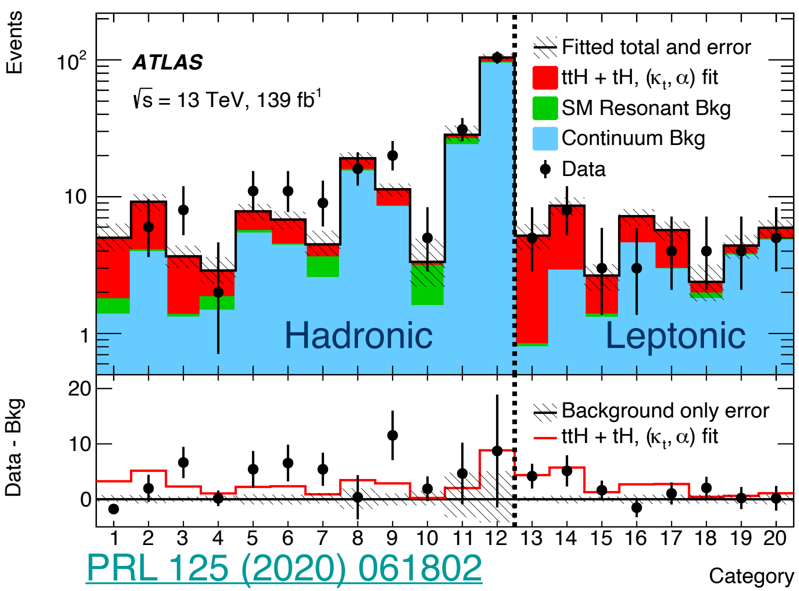


ttH and tH cross-section measurements

- **Single-channel ttH observation at 5.2σ,** assuming SM for other prod. modes

$$\mu = 1.43^{+0.33}_{-0.31}(\text{stat.})^{+0.21}_{-0.15}(\text{syst.})$$

- tH cross-section < 12×SM @95% CL



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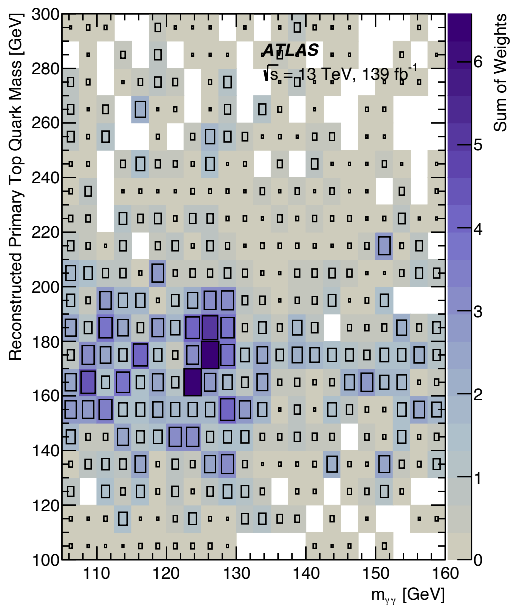
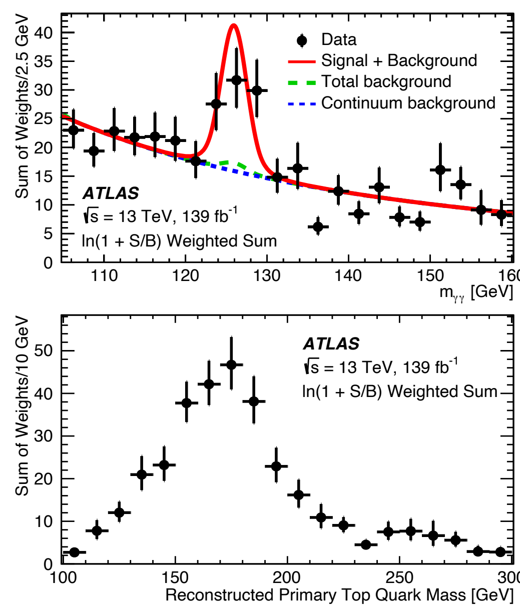
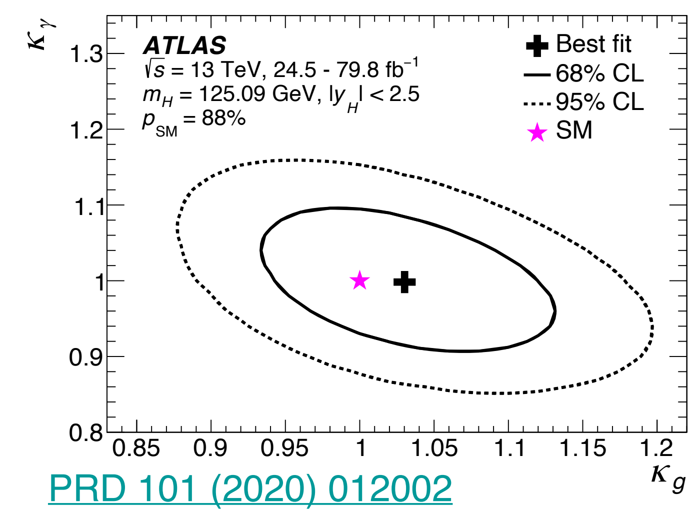


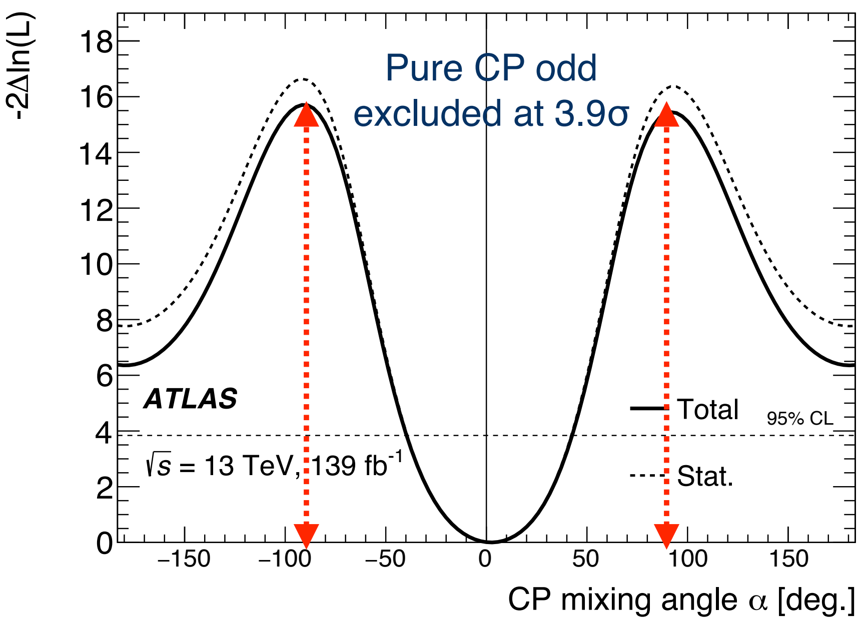


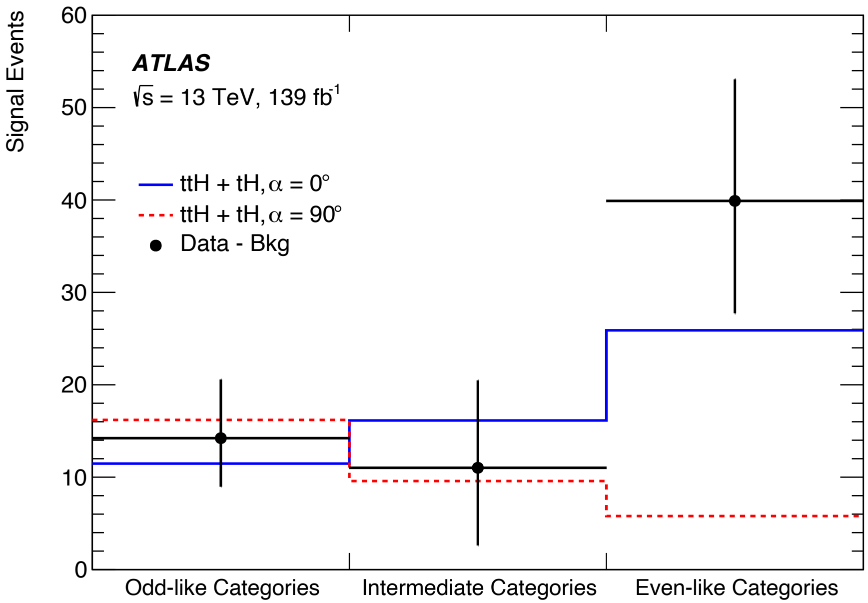
CP constraint: not resolve H→γγ/ggF loops

- Provide **direct** constrain mixing angle α using **only ttH and tH info**
  - Use κ_γ **vs** κ_g **contour (80 fb⁻¹)** to constrain H→γγ and ggF rates
- **|α| > 43°** excluded @95% CL **without assumption on** κ_t



PRD 101 (2020) 012002





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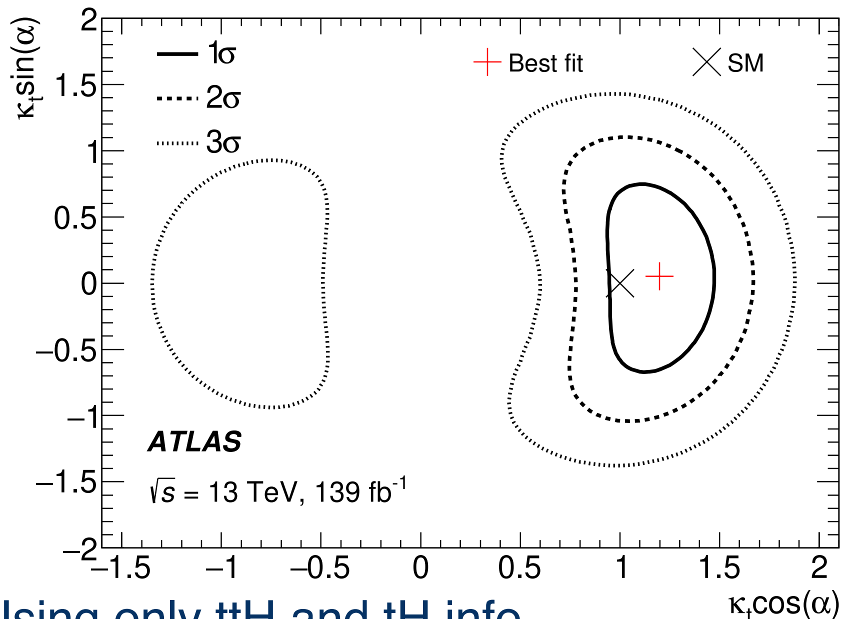
CP constraint: resolve H→γγ/ggF loops

- Assume potential new physics in H→γγ/ggF is only in t-H coupling, and can be parameterized as function of α and κ_t (Ellis et. al. JHEP 04 (2014) 004)

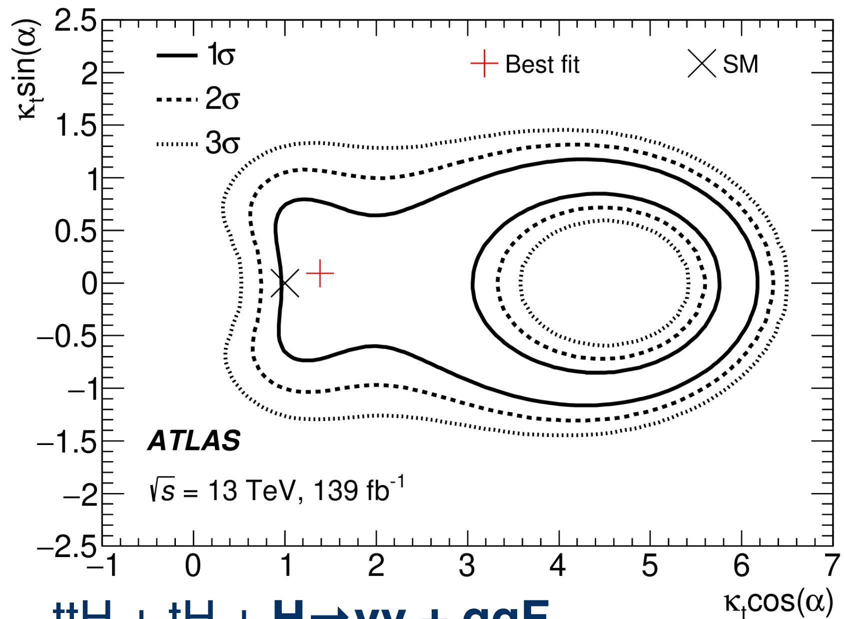
$$\kappa_g^2 = \kappa_t^2 \cos^2(\alpha) + 2.6\kappa_t^2 \sin^2(\alpha) + 0.11\kappa_t \cos(\alpha)(\kappa_t \cos(\alpha) - 1)$$
$$\kappa_\gamma^2 = (1.28 - 0.28\kappa_t \cos(\alpha))^2 + (0.43\kappa_t \sin(\alpha))^2$$

- Exclude **$|\alpha| > 43°$ @95% CL without assumption on κ_t**

PRL 125 (2020) 061802



Using only ttH and tH info



ttH + tH + **H→γγ + ggF**

Conclusions

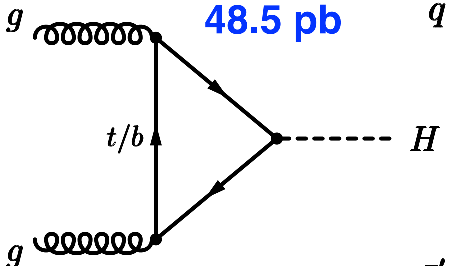
- CP properties of top Yukawa coupling studied with ATLAS experiment based on full Run 2 data
  - CMS results: PRL 125 (2020) 061801
  - No deviation from SM observed yet
  - Constraint limited by statistical uncertainty
- In the meantime, explore other Higgs decay channels (e.g. H→bb and multi-lepton), SM top processes (e.g. 4-top production PRD 99 (2019) 113003), and Higgs combination (using ggF and H→γγ rates + ttH rate & kinematics)

Backup

SM Higgs boson production at LHC

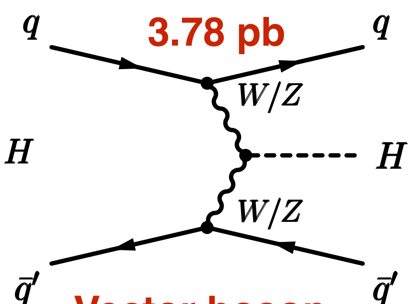
Main

48.5 pb



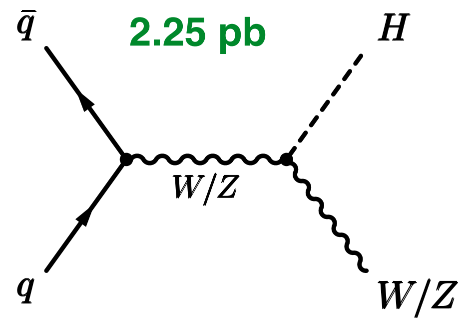
Gluon-fusion ggF (~87%)

3.78 pb



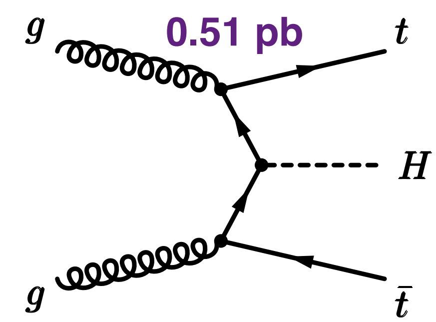
Vector boson fusion (VBF) (~7%)

2.25 pb



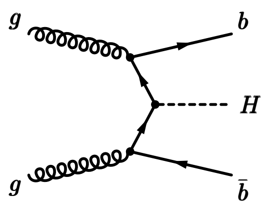
VH (~4%)

0.51 pb

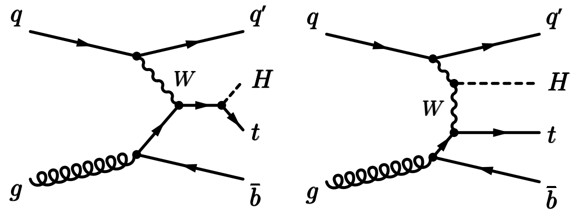


ttH (~1%)

Rare

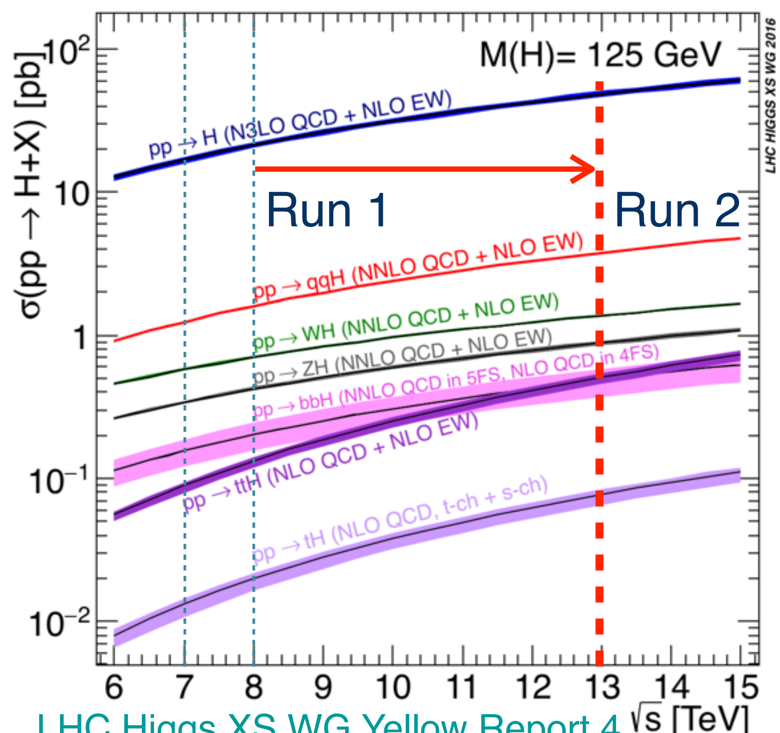


bbH (~1%) 0.49 pb



tH (~0.1%) 0.09 pb

- Distinct topology from each production mode
- Cross section of main production modes calculated with relatively high accuracy
- Rare production modes difficult to probe, but important for beyond the SM (BSM) scenarios

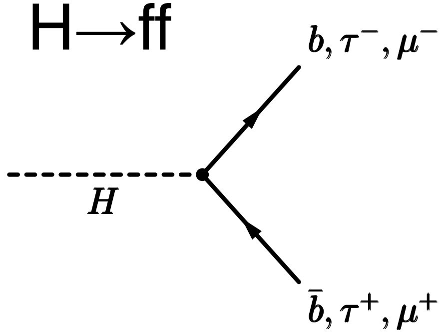


LHC Higgs XS WG Yellow Report 4

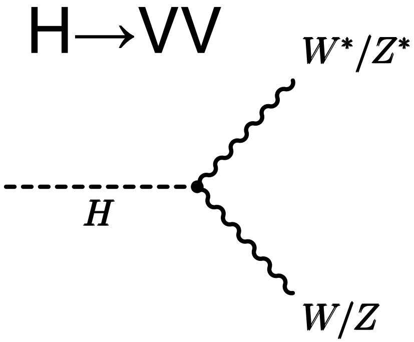
Higgs boson decays

- "Big five": **γγ** (0.23%), ZZ, WW, ττ, bb
- "Rare" channels: **μμ** (0.022%), Zγ, cc, etc.

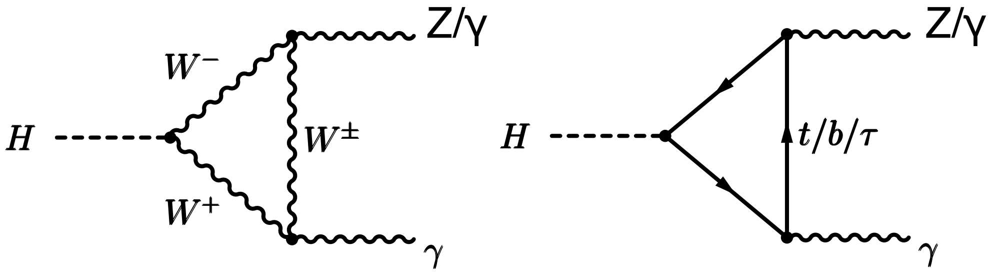
H→ff

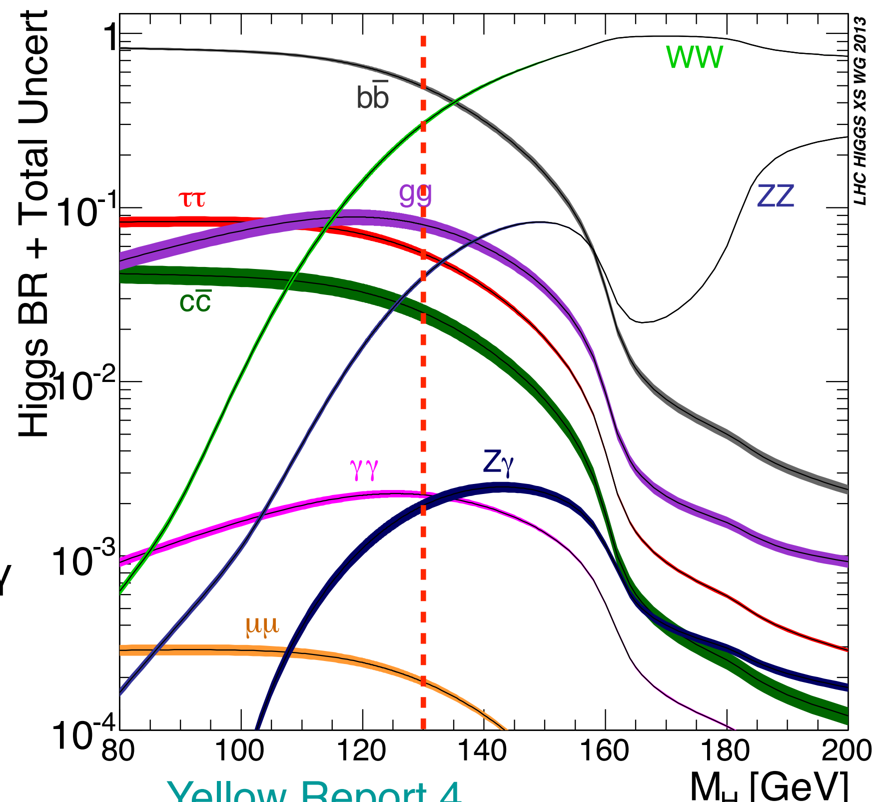


H→VV



H→γγ/Zγ





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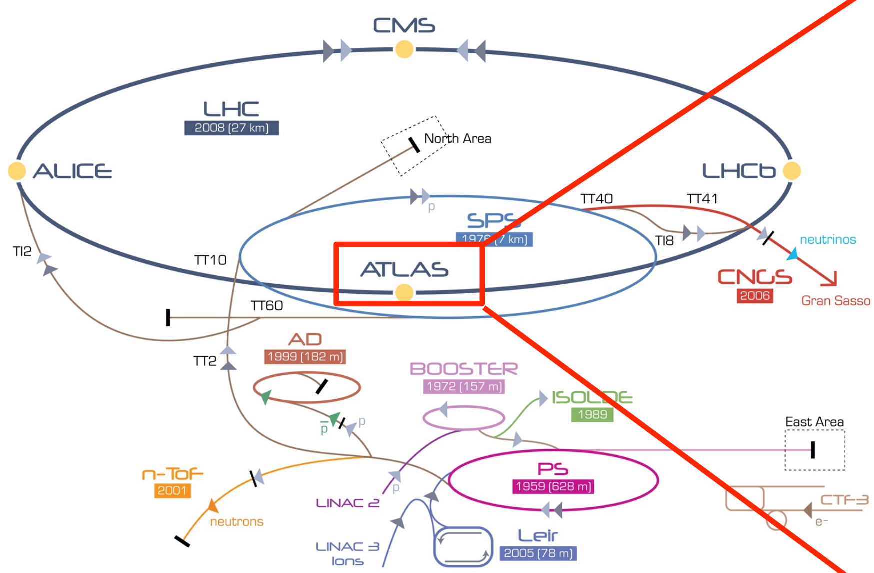
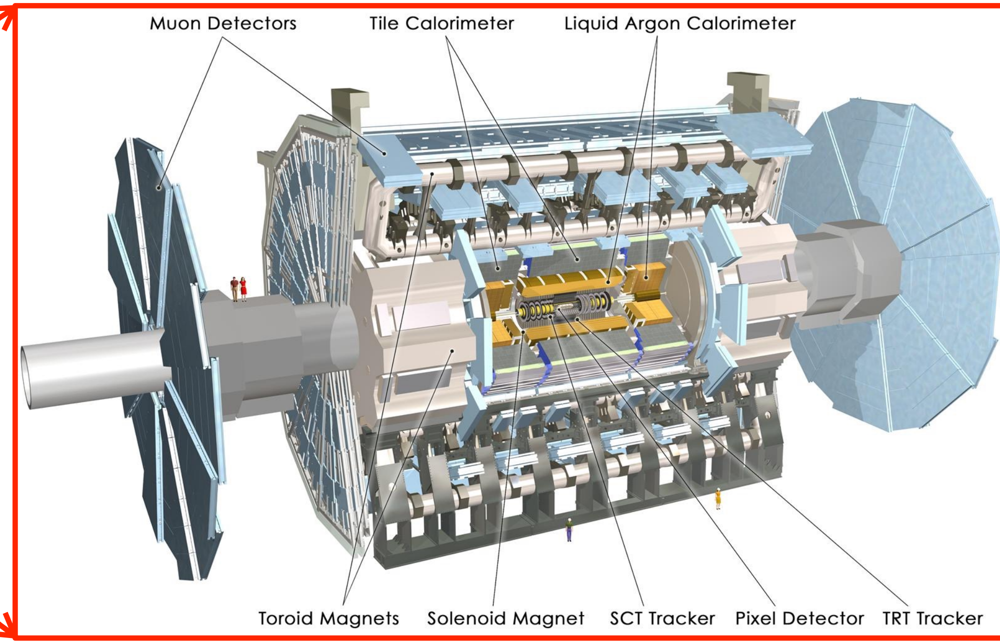
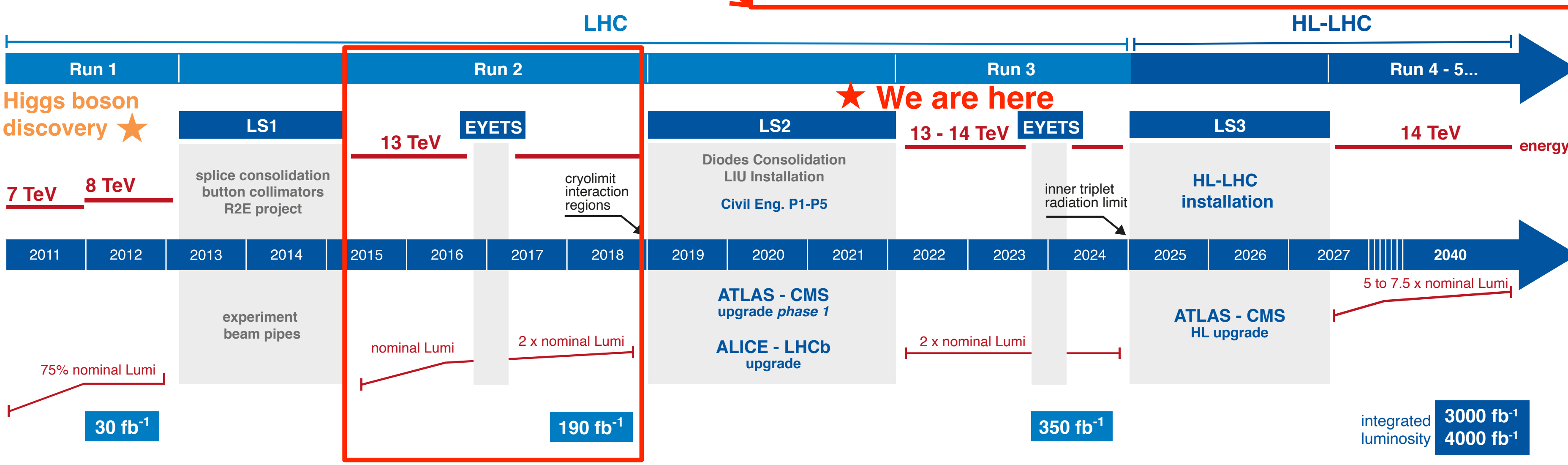
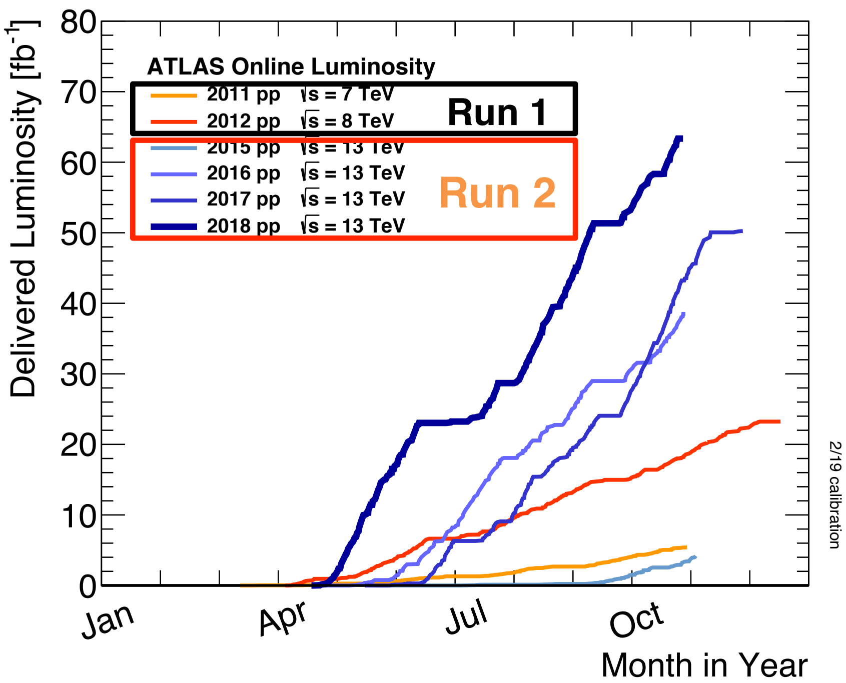
The ATLAS detector

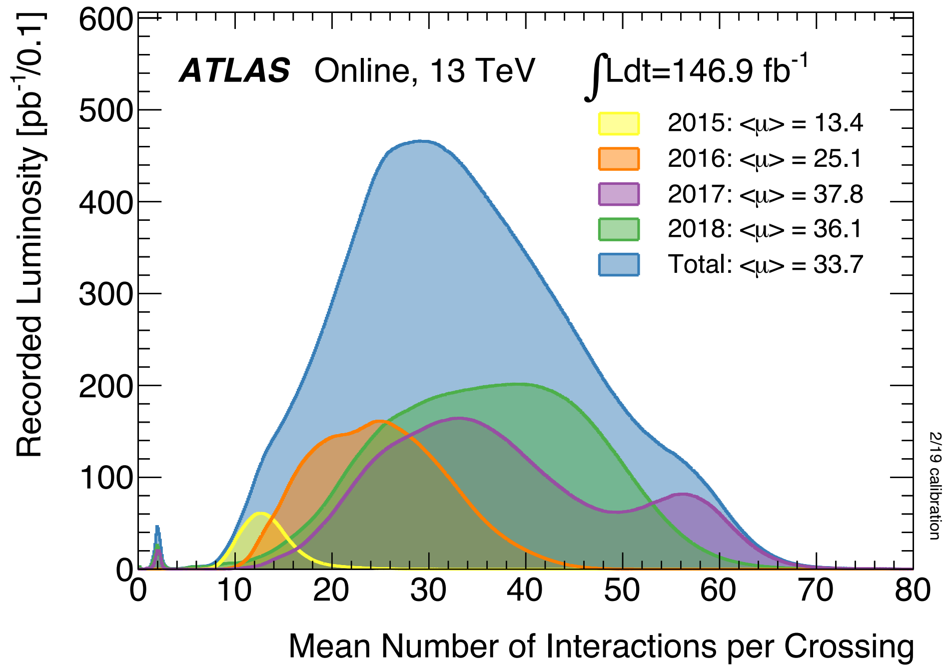






Run 2 data taking





- **139 fb^{-1}** of **13 TeV** proton-proton collision data collected for physics by ATLAS detector
  - Average 34 interactions per bunch crossing
- Thanks to the excellent LHC performance and smooth operation of ATLAS detector

Data & signal MC samples for ttH CP analysis

- **Data**: full Run 2 dataset of 139 fb^{-1}
- **ttH/tH signal**: **NLO MG5_aMC+Pythia8** using **Higgs Characterization (HC) model**
  - ttH: $\boldsymbol{\kappa_t = 1}$, $\alpha = 0°, 15°, 30°, \ldots, 90°$
  - tHjb/tWH: sample generated with both $\boldsymbol{\kappa_t = 1}$ **and ≠ 1** at different mixing angles. $\kappa_W = 1$
- **ggF signal**: PowHeg NNLOPS
  - Kinematic dependence on CP mixing checked to be well-covered by syst. using **MG_aMC HC model ggF+2j** samples
- **Other Higgs production modes**: same as typical ATLAS Run 2 Higgs analyses