



# Higgs Width and CP measurements from ATLAS

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QCD@LHC 2026 at the University of Oxford

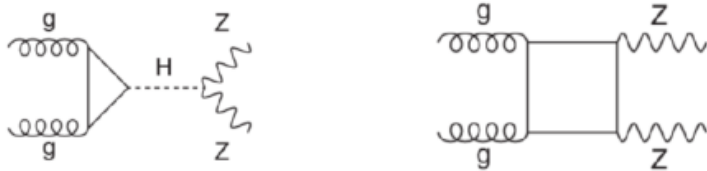


# Properties and interaction structure of the Higgs boson

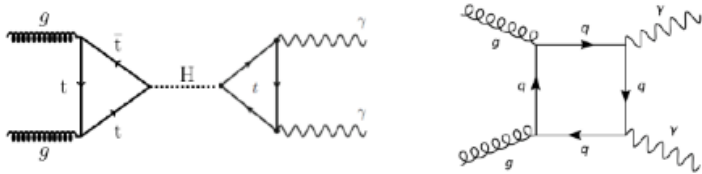
- **Mass and quantum numbers:**
  - scalar with  $J^P = 0^+$  ([2013](#))
  - $m_H = 125.11 \pm 0.11 \text{ GeV}$  ([2023](#))

## • Total width

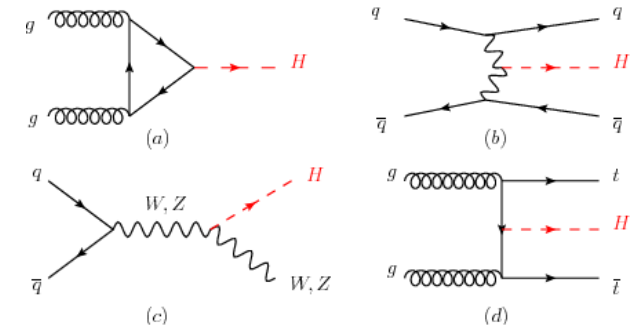
- On/off-shell rate comparison ([2026](#))
  - $\Gamma_H = 3.6^{+2.1}_{-1.6} \text{ MeV}$



- On-shell  $H \rightarrow \gamma\gamma$  sig-bkg interference ([2026](#))

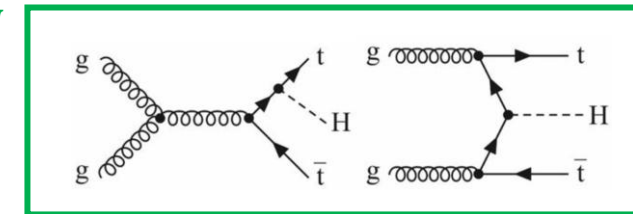


- **Interaction structure**
- **HVV**: CP and polarization
  - Run 2 HVV combination ([2026](#))
    - $\tau\tau, WW^*, \gamma\gamma, ZZ^*, WH(b\bar{b})$
  - Run 2+3 VBF  $H \rightarrow \gamma\gamma$  ([2026](#))

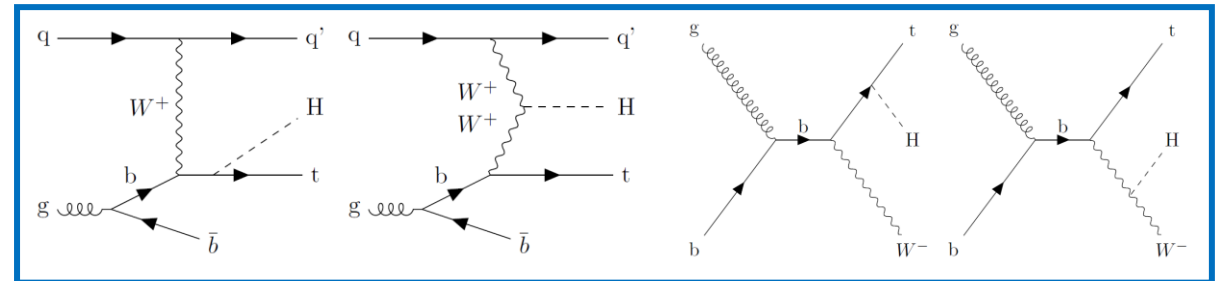


- **$t\bar{t}H$** : Yukawa CP structure
  - Run 2+3  $t\bar{t}H/tH, H \rightarrow \gamma\gamma$  ([2026](#))

$t\bar{t}H$



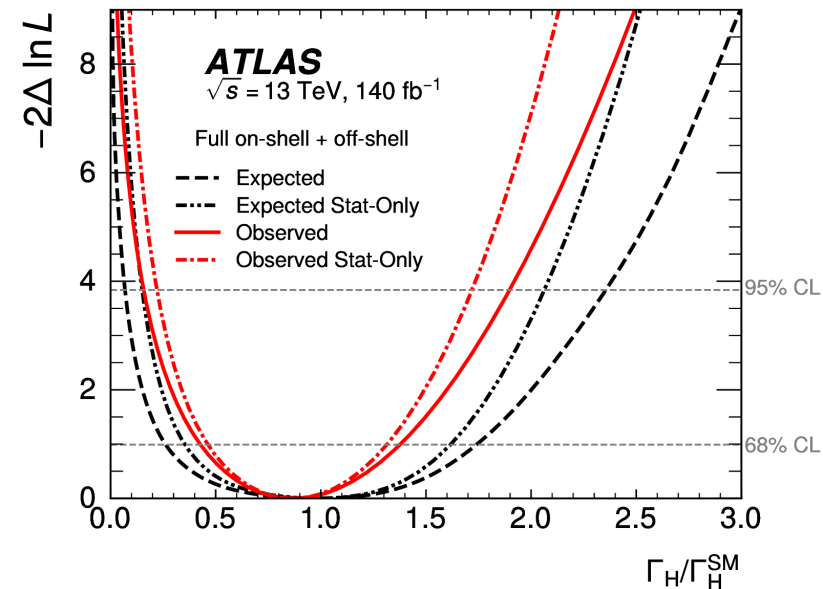
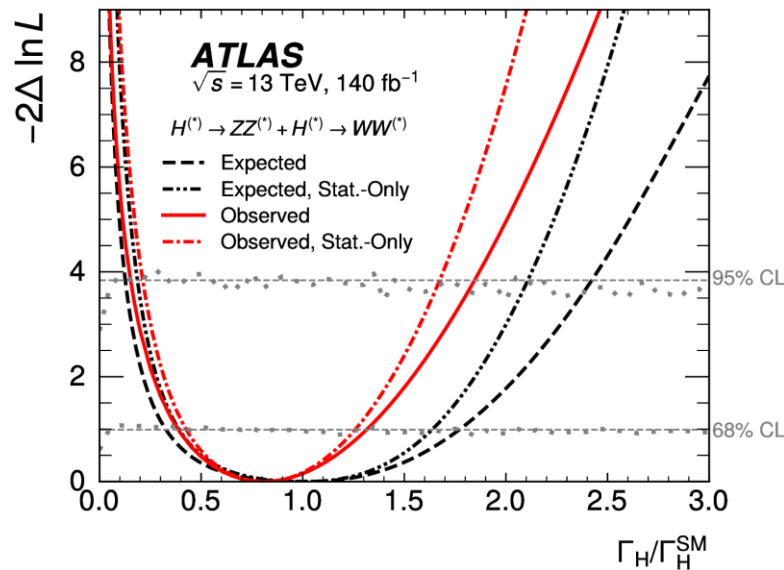
$tH$



[Phys.Rev.Lett.90:252001,2003](#) [PhysRevD.88.013004](#)

# Run 2 Combination Results on $\Gamma_H$

- Global Run 2 Higgs combination:  $\mu = 0.990_{-0.051}^{+0.053}$ , overall Higgs rate consistent with the SM
- Higgs Width:
  - $ZZ/WW$  on- and off-shell:  $\Gamma_H = 3.3_{-1.7}^{+2.1} \text{ MeV}$  ( $4.1_{-2.7}^{+3.2} \text{ MeV}$  expected)
  - Full on-shell +  $ZZ/WW$  off-shell:  $\Gamma_H = 3.6_{-1.6}^{+2.1} \text{ MeV}$  ( $4.1_{-3.0}^{+3.0} \text{ MeV}$  expected)
- $H^* \rightarrow ZZ \rightarrow 4\ell$  input uses NSBI: unbinned inference using NN-estimated event likelihood ratios



# Higgs Width from On-Shell $H \rightarrow \gamma\gamma$ Interference

- Indirect constraints on  $\Gamma_H$  by comparing on-shell and off-shell  $H$  production rates ( $H \rightarrow WW/ZZ$ )
  - Need to assume Higgs coupling to  $g$  and  $V$  are identical on-shell and off-shell
- On-shell constraint: **interference** between resonance and continuum  not needed
  - $[gg \rightarrow H \rightarrow \gamma\gamma \text{ and } gg \rightarrow \gamma\gamma]$  (leading) and  $[qg \rightarrow Hq \rightarrow \gamma\gamma q \text{ and } qg \rightarrow \gamma\gamma q]$

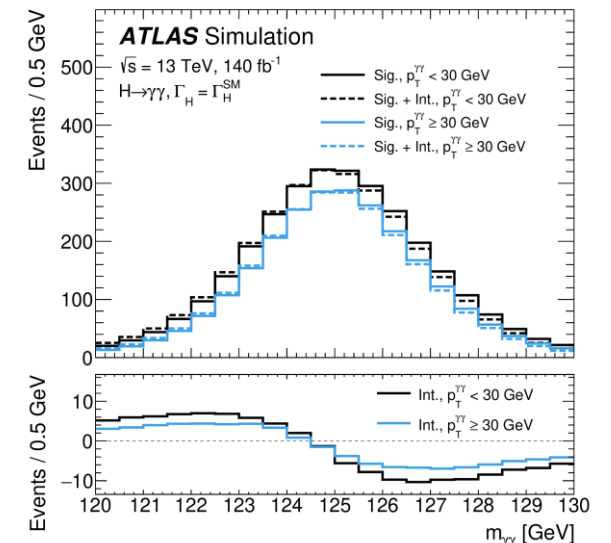
$$\mathcal{M}_{gg \rightarrow \gamma\gamma} = \frac{\mathcal{M}_{\text{sig}}}{m_{\gamma\gamma}^2 - m_H^2 + i\Gamma_H m_H} + \mathcal{M}_{\text{bkg}} \Rightarrow |\mathcal{M}_{gg \rightarrow \gamma\gamma}|^2 = \frac{|\mathcal{M}_{\text{sig}}|^2}{(m_{\gamma\gamma}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2} + |\mathcal{M}_{\text{bkg}}|^2 + I,$$

$I = \text{Antisymmetric about } m_{\gamma\gamma}^2 - m_H^2 + \text{Symmetric about } m_{\gamma\gamma}^2 - m_H^2$  ( $\sim 2\%$  signal yield reduction)

- On-shell rate scales as  $\frac{c_g^2 c_\gamma^2}{\Gamma_H}$ ; interf. rate scales differently as  $c_g c_\gamma$

$$\Rightarrow I/I_{\text{SM}} = \sqrt{\mu \Gamma_H / \Gamma_H^{\text{SM}}}$$

- Interference-induced mass shift larger at low  $p_T^{\gamma\gamma}$

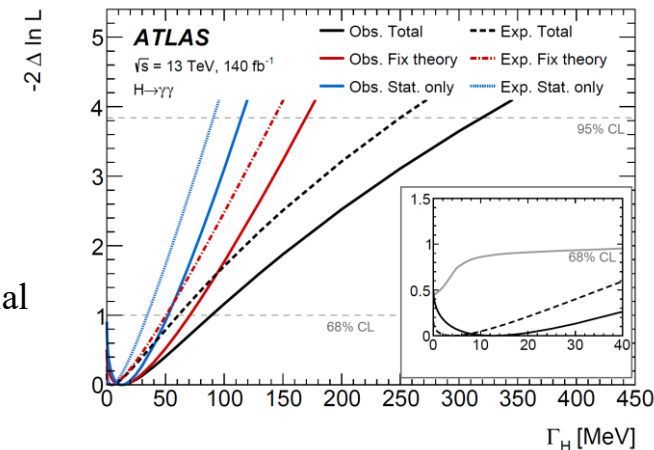


# Higgs Width from On-Shell $H \rightarrow \gamma\gamma$ Interference

- Two categories  $p_T^{\gamma\gamma} < 30\text{GeV}$  and  $p_T^{\gamma\gamma} > 30\text{GeV}$

$$F^c(m_{\gamma\gamma}) = \underbrace{\mu K_S N_S^c f_S^c}_{\text{signal strength Double Side Crystal Ball}} + \underbrace{\sqrt{\frac{\mu\Gamma_H}{\Gamma_H^{\text{SM}}}} \left[ N_{I,gg}^c f_{I,gg}^c + N_{I,qg}^c f_{I,qg}^c \right]}_{\text{interference opposite sign sum of two DSCBs}} + \underbrace{N_B^c f_B^c}_{\text{continuum background exponentiated 2nd order polynomial}}$$

$$f_I^c(m_{\gamma\gamma}) = n_+^c f_+^c(m_{\gamma\gamma}) + n_-^c f_-^c(m_{\gamma\gamma})$$



- Simultaneous maximum-likelihood fit to both categories

- $\Gamma_H$ ; Signal strength; background modeling parameters
- Nuisance parameters including constraints on Higgs mass

- Observed (expected) upper limit:

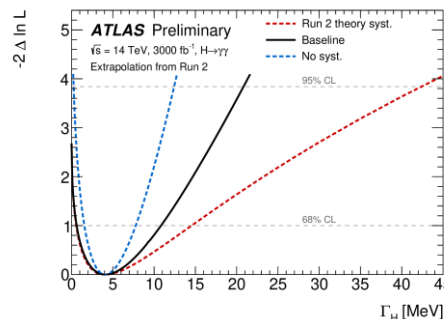
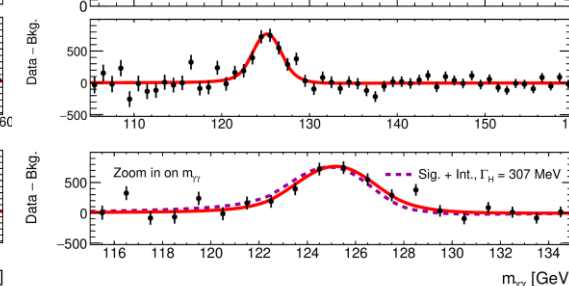
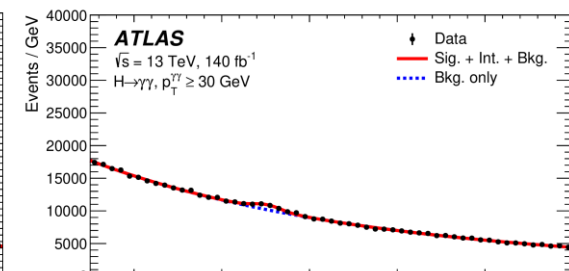
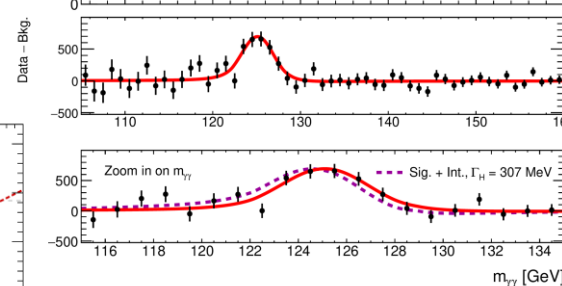
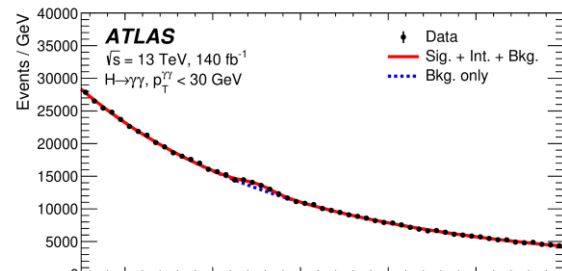
- $\Gamma_H < 307(258)\text{ MeV}$  at 95% CL,  $\sim 75(63) \times \Gamma_{SM}$

- Dominant uncertainties

- Theory uncertainty on  $gg$  interference normalization
- External Higgs mass uncertainty

- HL-LHC projection:

- $\Gamma_H < 21\text{MeV}$  at 95% CL with  $3000\text{ fb}^{-1}$



# CP Structure of $HVV$ interaction: Run 2 Combination

- In SMEFT, dim-6 CP-violating operators that describe  $HVV$  interaction

- $\mathcal{L}_{\text{SMEFT}} = \mathcal{L} + \frac{1}{\Lambda^2} (c_{H\tilde{W}} \hat{\mathcal{O}}_{H\tilde{W}} + c_{H\tilde{B}} \hat{\mathcal{O}}_{H\tilde{B}} + c_{H\tilde{W}B} \hat{\mathcal{O}}_{H\tilde{W}B})$  in Warsaw basis

( $\Lambda = 1\text{TeV}$ )

- $|\mathcal{M}_{\text{SMEFT}}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \underbrace{\sum_i \frac{2c_i}{\Lambda^2} \text{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{CPodd}})}_{\text{Linear in } c_i; \text{ affects shape}} + \underbrace{\sum_{i,j} \frac{c_i c_j}{\Lambda^4} |\mathcal{M}_{\text{CPodd}}|^2}_{\text{Quadratic in } c_i; \text{ affects inclusive cross-section}}$

Linear in  $c_i$ ; affects shape

Quadratic in  $c_i$ ; affects inclusive cross-section

- $\gamma\gamma, \tau\tau, ZZ^*$  channels:

- Optimal Observable ( $\mathcal{OO}$ ):  $2\text{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{BSM}}) / |\mathcal{M}_{\text{SM}}|^2$

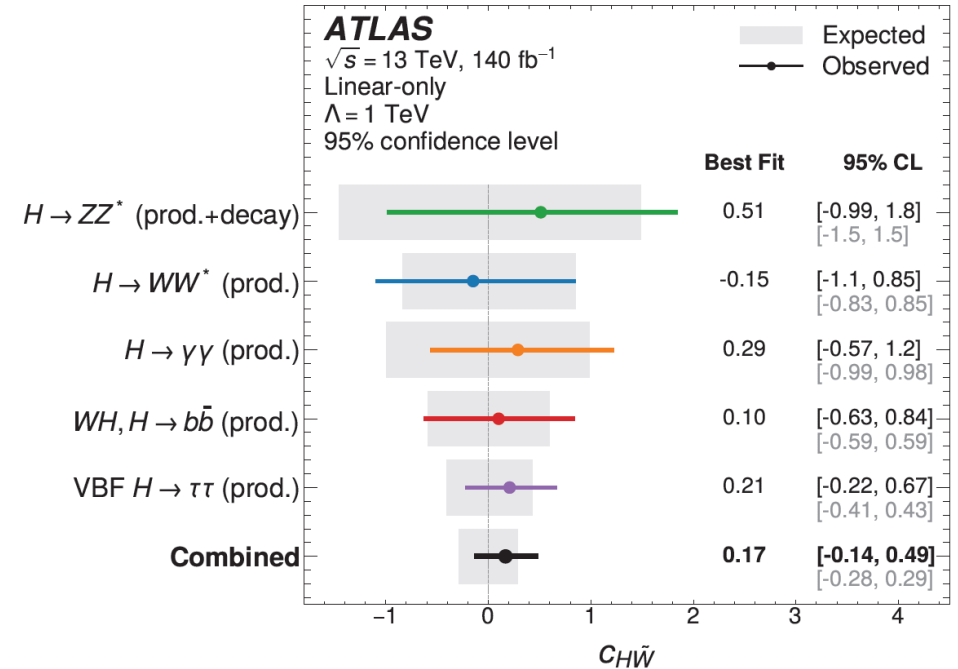
- $WH, H \rightarrow b\bar{b}$  channel:

- two bins of  $Q_\ell \cos \delta^+$   $\frac{\mathbf{p}_\ell^{(W)} \cdot (\mathbf{p}_H \times \mathbf{p}_W)}{|\mathbf{p}_\ell^{(W)}| \cdot |\mathbf{p}_H \times \mathbf{p}_W|}$

- $WW$  channel:  $\Delta\phi_{jj}$

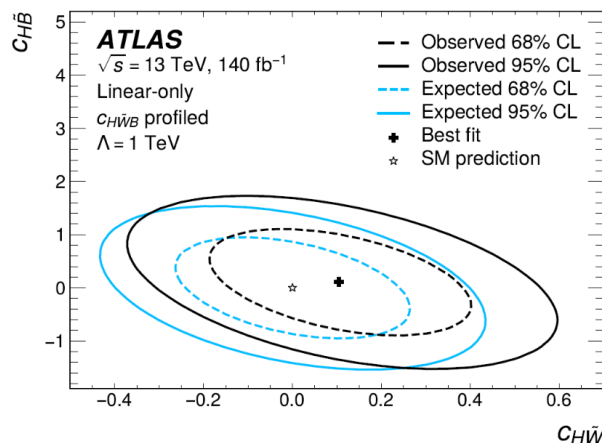
- $\Delta\phi$  between the  $\eta$ -ordered two (VBF) jets

- Limits on  $c_{H\tilde{W}}$  in single parameter fit improved by  
> 40% on the best individual channel results

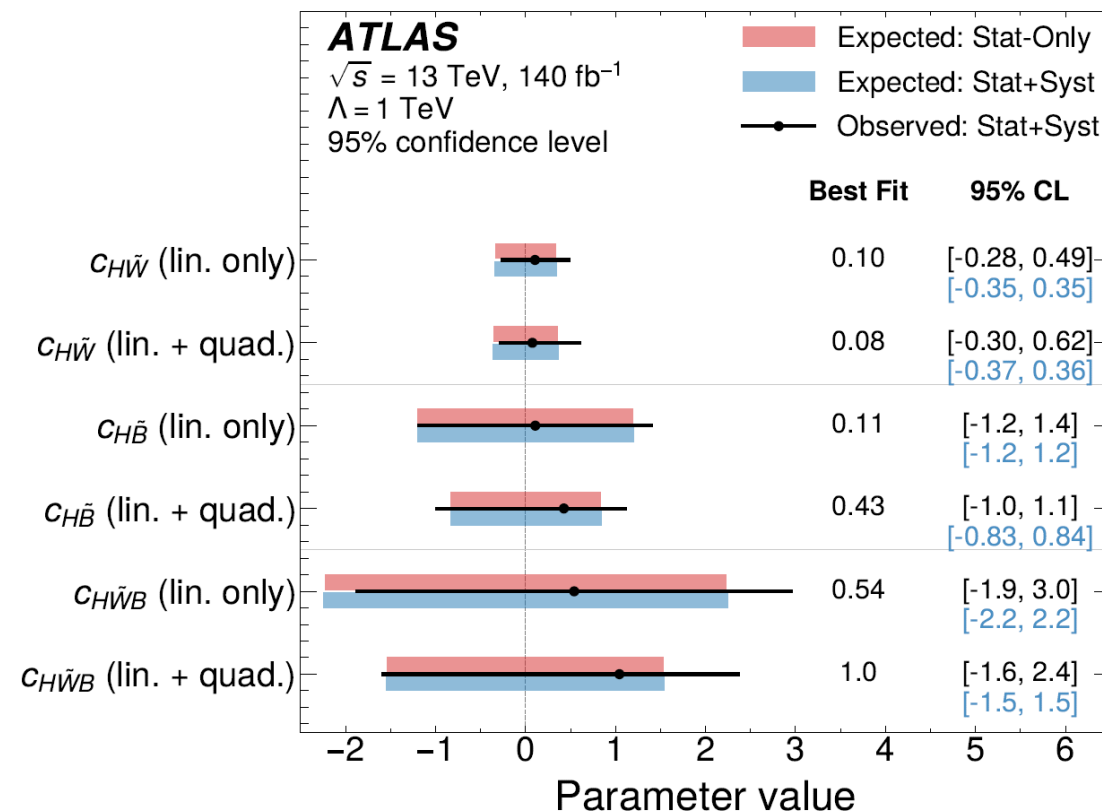


# CP Structure of $HVV$ interaction: Run 2 Combination

- First simultaneous constraint of  $c_{H\tilde{W}}$ ,  $c_{HB}$ ,  $c_{H\tilde{W}B}$ 
  - fewer assumptions than the single parameter interpretation
  - correlations weaken the individual constraints

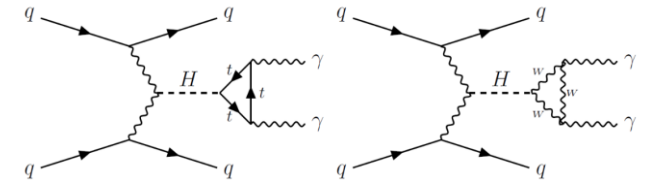


- Linear-only and linear+quadratic fit give compatible constraints
- No evidence of CP violation found
- Statistically dominated

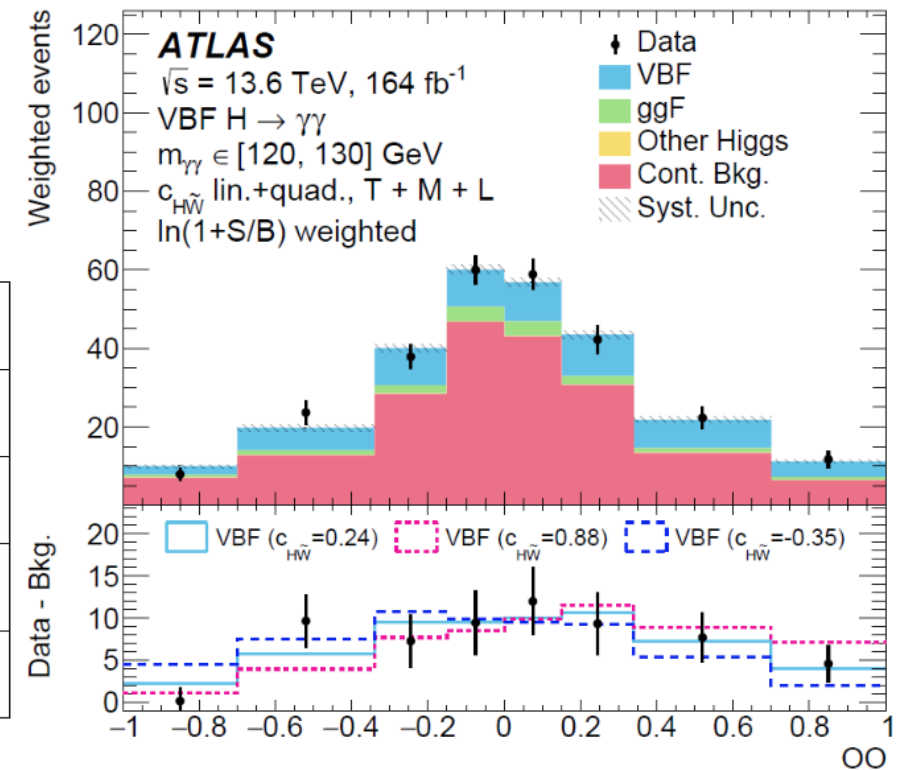
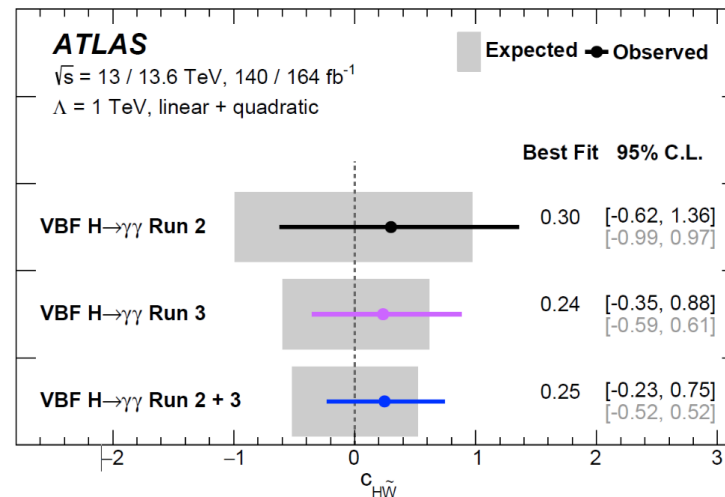


Most stringent constraints to date

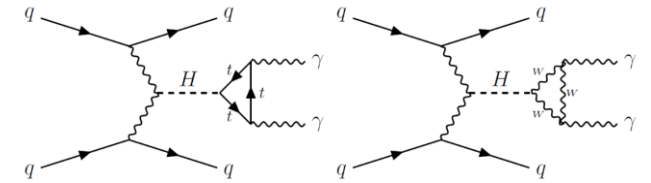
# Partial Run 3 VBF $H \rightarrow \gamma\gamma$



- Performed (1) limit setting on  $c_{H\tilde{W}}$  and (2) testing longitudinal/transverse HVV couplings
- Multiclass NN classifier labels: VBF Higgs, ggF Higgs, non-resonant  $\gamma\gamma$ +jets
  - Continuum sample augmented with a generative model trained from data
- Using optimal observable ( $\mathcal{OO}$ ) for the  $c_{H\tilde{W}}$  study
- A 38% improvement to the run 2 analogous result
  - 29% due to analysis strategy
- Combining with run 2 gives
- $c_{H\tilde{W}} \in [-0.23, 0.75]$

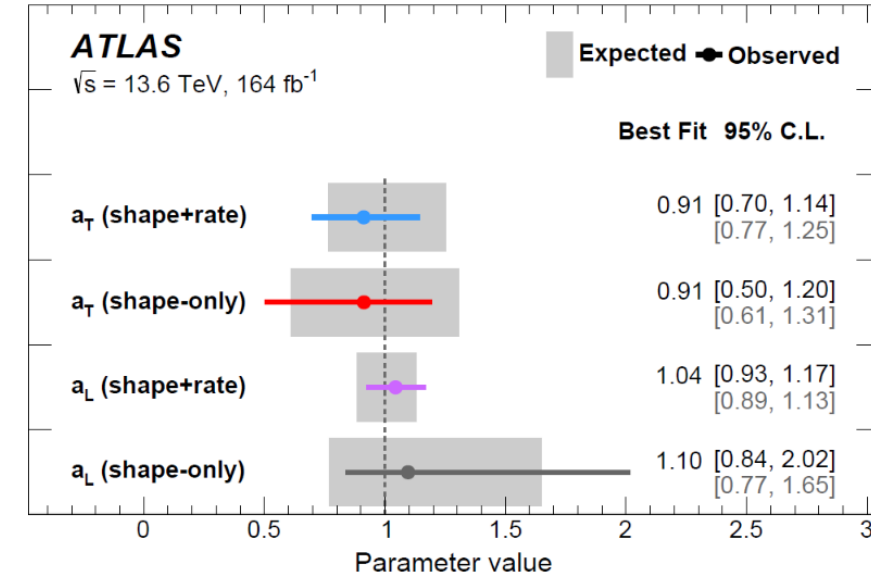
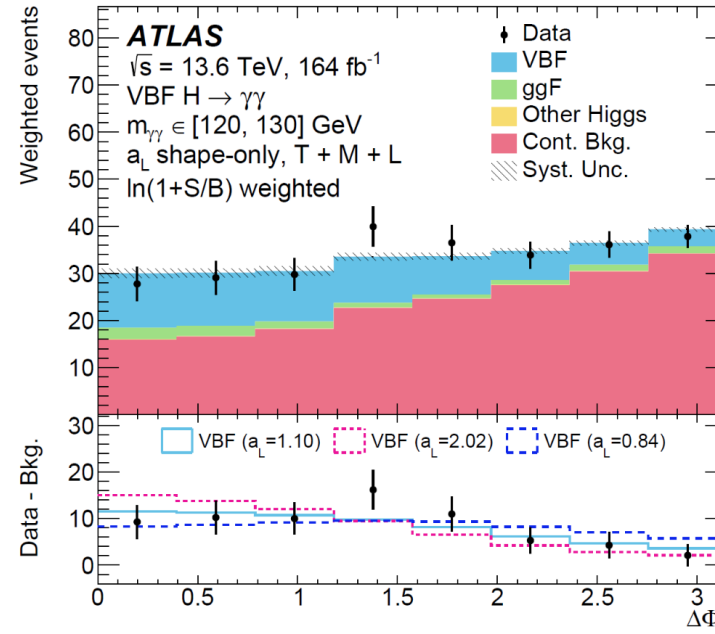
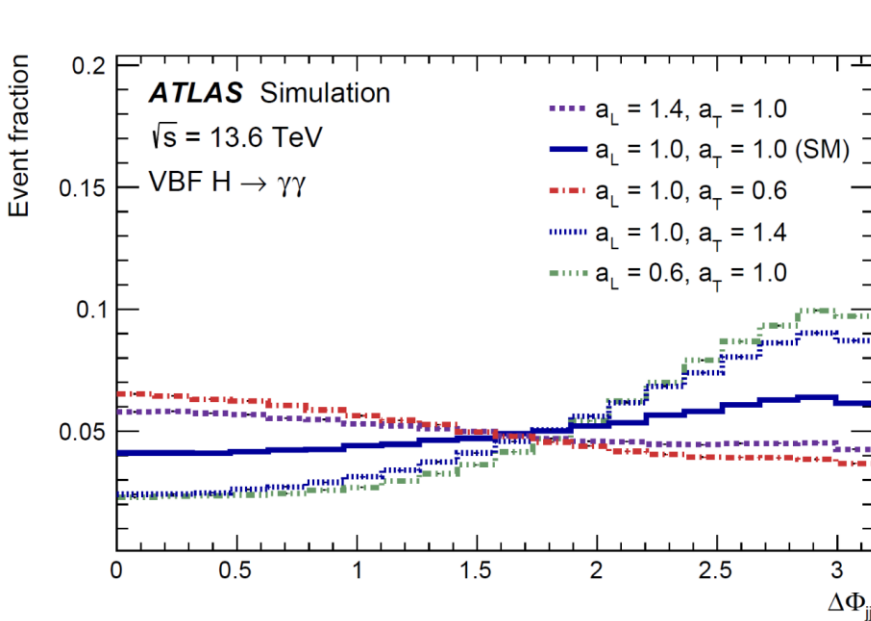


# Partial Run 3 VBF $H \rightarrow \gamma\gamma$



$$a_L = \frac{g_{H V_L V_L}}{g_{H V V}}, \quad a_T = \frac{g_{H V_T V_T}}{g_{H V V}}$$

- Polarization dependent HVV coupling strength
  - First measurement of  $a_L, a_T$  in this channel
- Fit  $\Delta\phi_{jj}$ : (signed) azimuthal difference between the two VBF jets
- Shape-only and shape + rate interpretations:
  - Rate info further constraints  $a_L$  by a lot, whereas the shape of  $\Delta\phi_{jj}$  provides most of  $a_T$ 's sensitivity

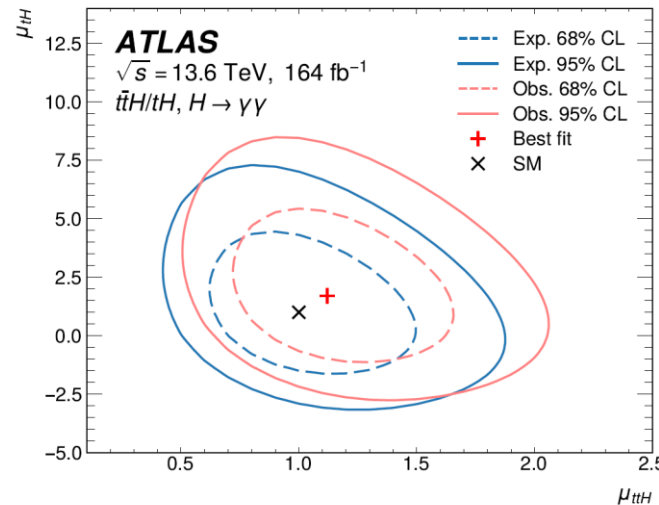
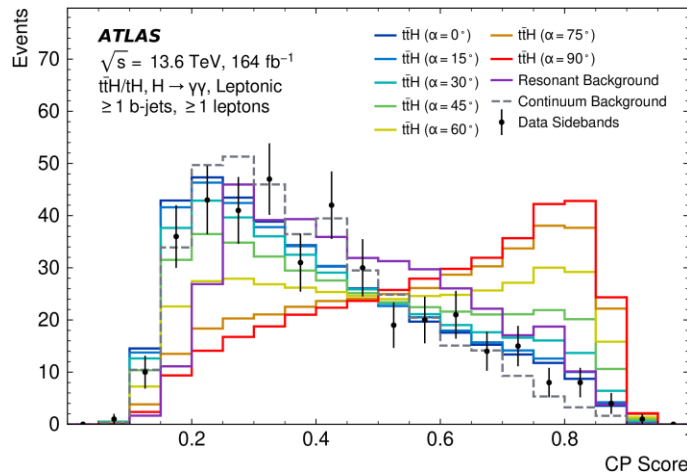


# Partial Run 3 $t\bar{t}H/tH \ H \rightarrow \gamma\gamma$

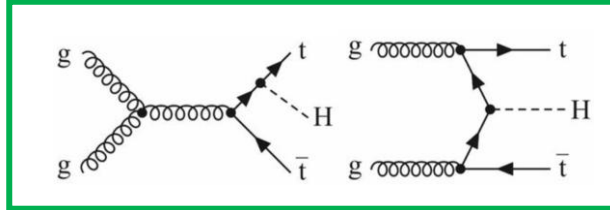
- $t\bar{t}H/tH$  provide direct access to Higgs-top Yukawa interaction:

$$\text{SM: } \kappa_t = 1, \alpha = 0 \quad \mathcal{L} = -\frac{m_t}{v} \left\{ \bar{\psi}_t \kappa_t [\cos(\alpha) + i \sin(\alpha) \gamma_5] \psi_t \right\} H$$

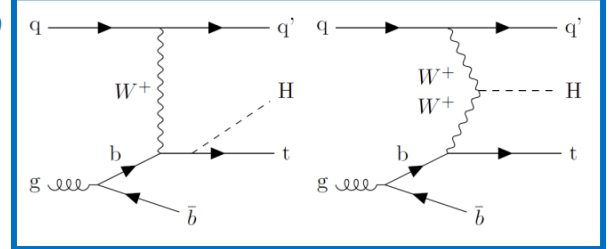
- Two GNNs:
  - Multiclass GNN labels  $t\bar{t}H$ ,  $tWH$ ,  $tHjb$ ; resonant bkg; continuum bkg
  - Binary CP GNN discriminant
  - GNN classification reduced correlation (-28%) between fitted  $t\bar{t}H$  and  $tH$  rates



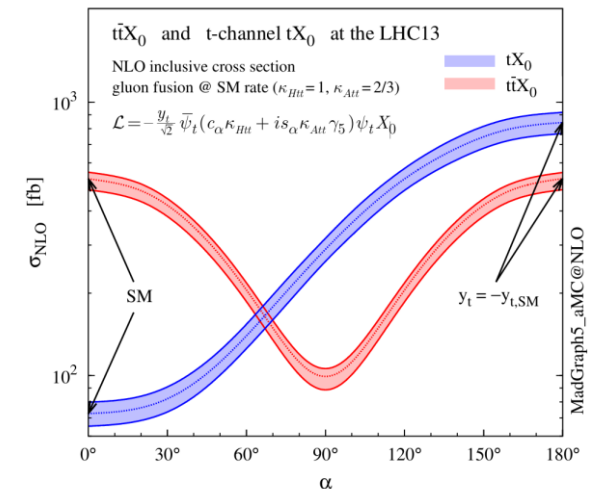
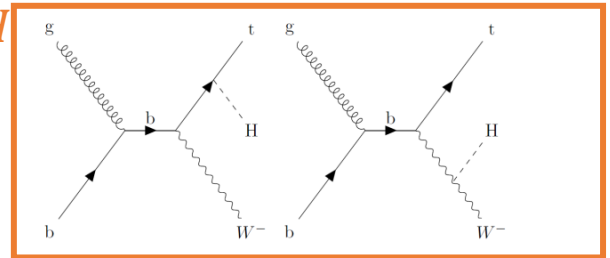
$t\bar{t}H$



$tHjb$



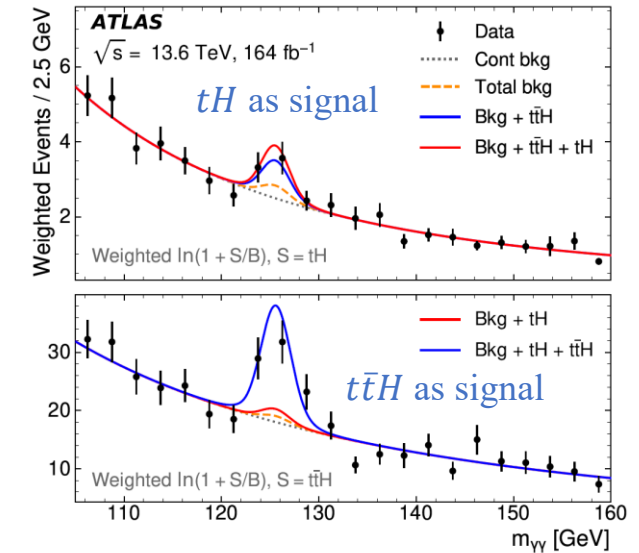
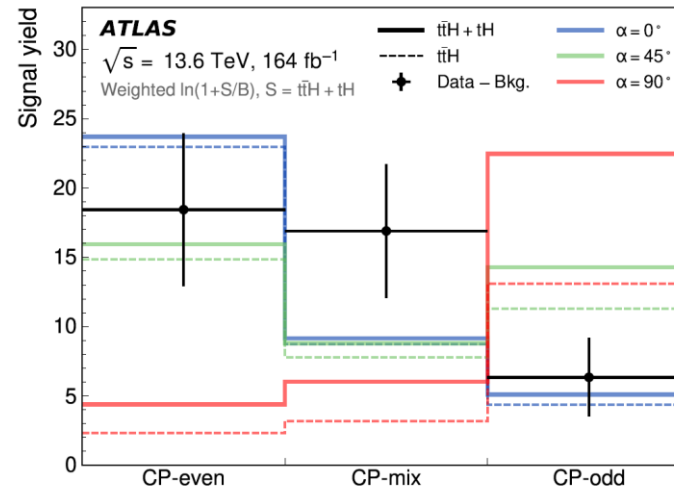
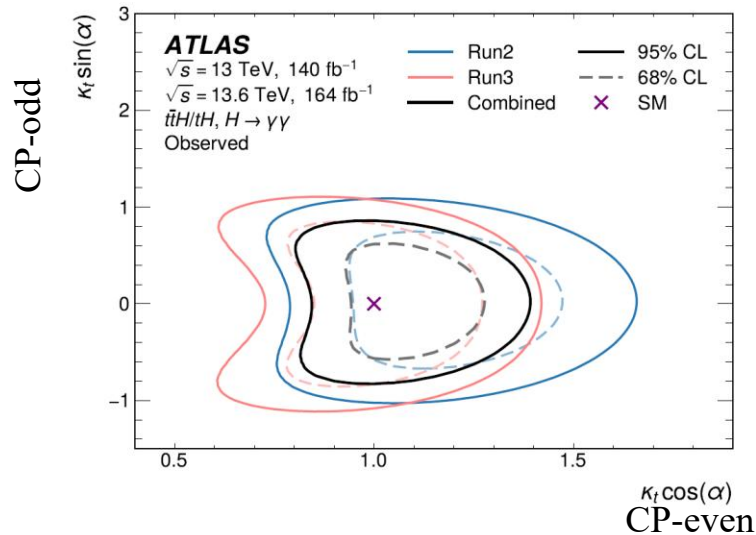
$tWH$



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# Partial Run 3 $t\bar{t}H/tH \ H \rightarrow \gamma\gamma$

- Fit simultaneously for  $(\kappa_t, \alpha)$ 
  - Run 3:  $|\alpha| > 53^\circ$  excluded at 95% CL
  - Run 2 + Run 3:  $|\alpha| > 38^\circ$  excluded at 95% CL
- Pure CP odd coupling excluded at  $5.8\sigma$
- Strongest direct constraint on the CP structure of the Higgs–top Yukawa interaction to date
- Measurement remains statistically limited



# Summary and Outlook

- No evidence for non-SM Higgs interaction structure
  - All measurements remain consistent with a CP-even SM Higgs boson with CP-even couplings
- Higgs width
  - New on-shell  $H \rightarrow \gamma\gamma$  measurement gives  $\Gamma_H < 307\text{MeV}$  (95% CL), a complementary constraint without assuming identical on-/off-shell Higgs couplings
- $HVV$ 
  - Run 2 combination gives the most stringent constraint on the three CP-odd Wilson coefficients
  - Run 3 VBF  $H \rightarrow \gamma\gamma$  has improved CP sensitivity on  $c_{H\tilde{W}}$  and the first  $a_L, a_T$  measurement in this channel
- $Htt$ :
  - Run 2+3  $ttH/tH, H \rightarrow \gamma\gamma$ :  $|\alpha| > 38^\circ$  excluded at 95% CL
  - Pure CP-odd top Yukawa excluded at  $5.8\sigma$ , best constraint to date
- Many key measurements remain statistics limited
  - Look forward to results from full run 3 data + improved analysis techniques

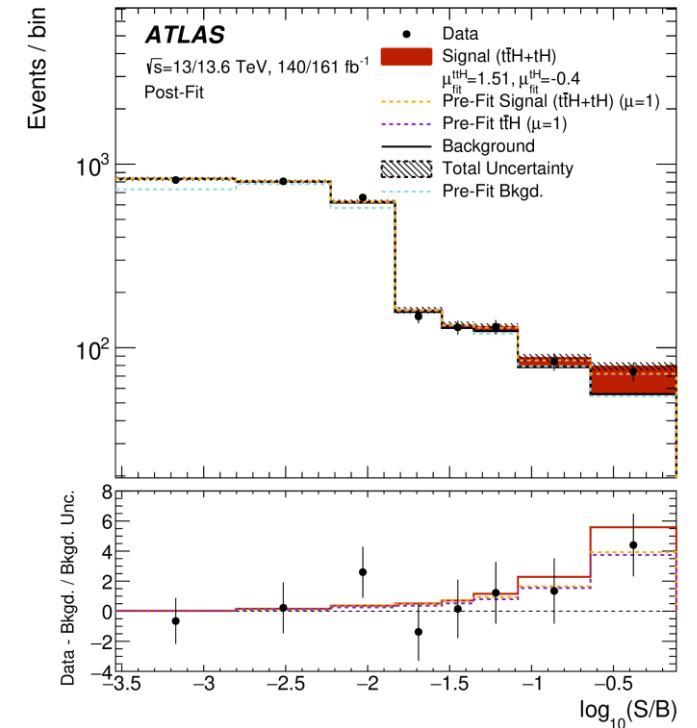
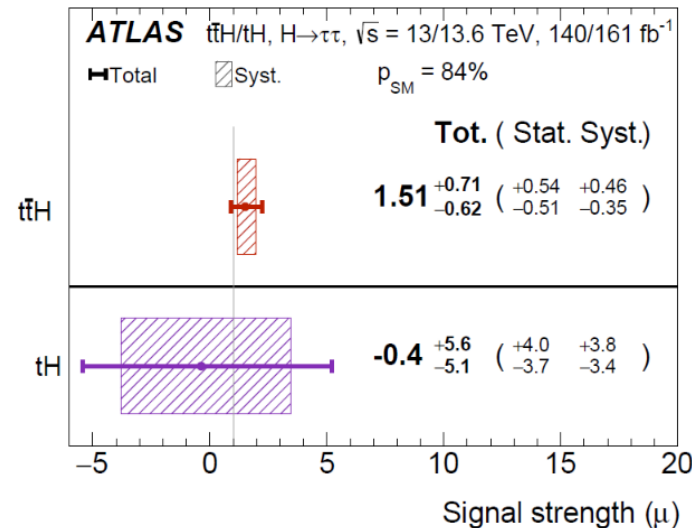
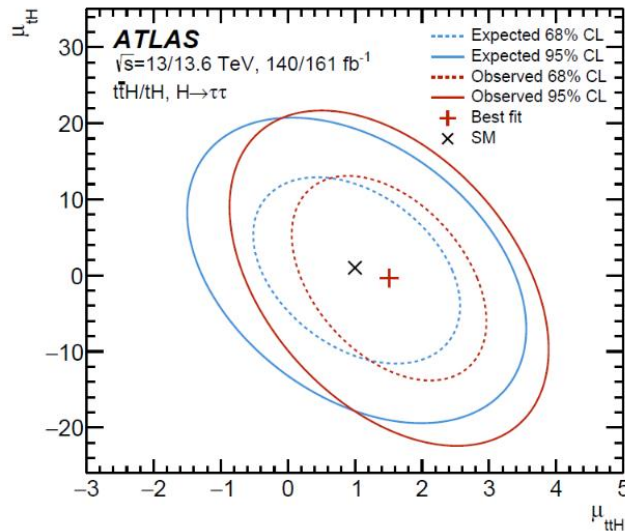
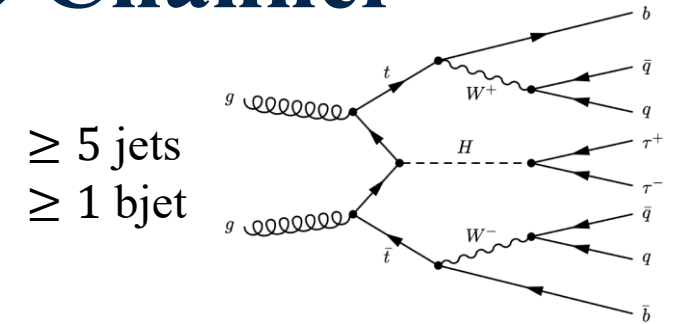


# Backup slides

# Run 2 + partial Run 3

## $t\bar{t}H, tH$ production in $H \rightarrow \tau\tau$ Channel

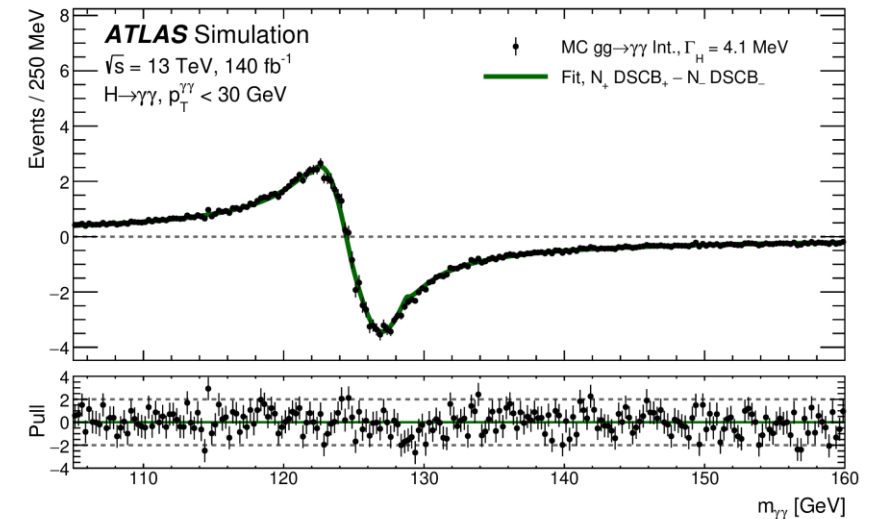
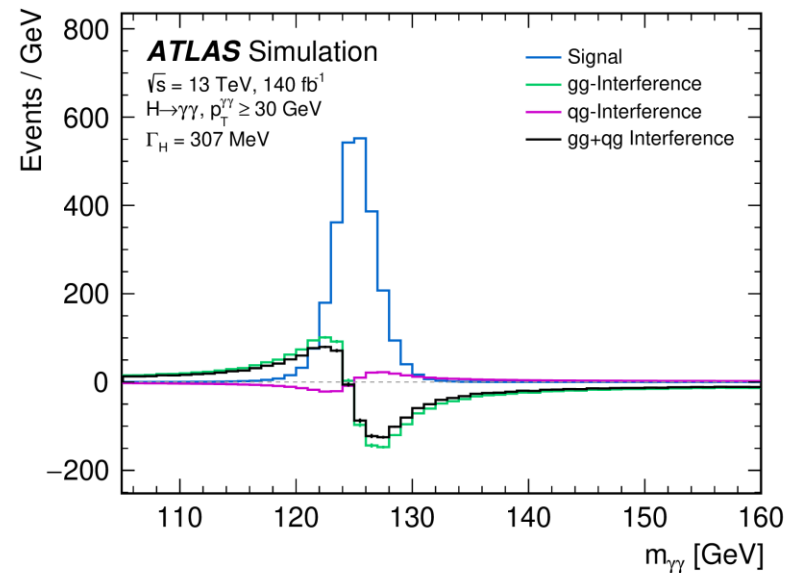
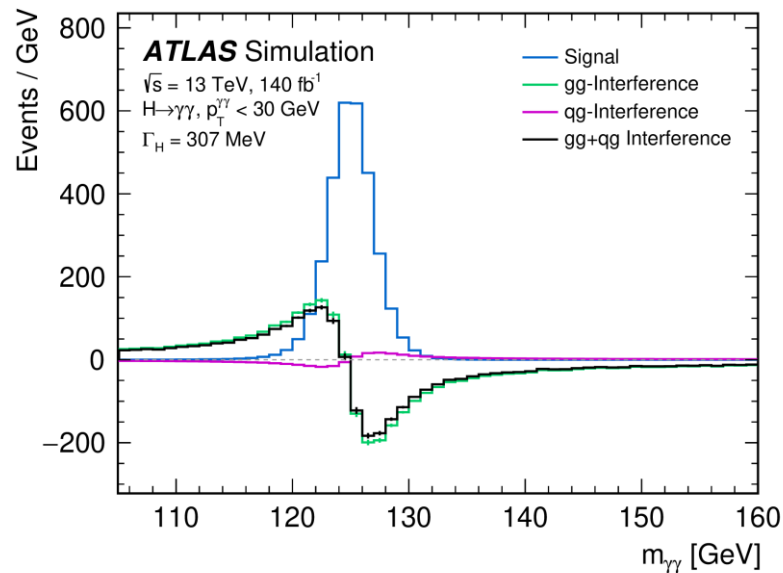
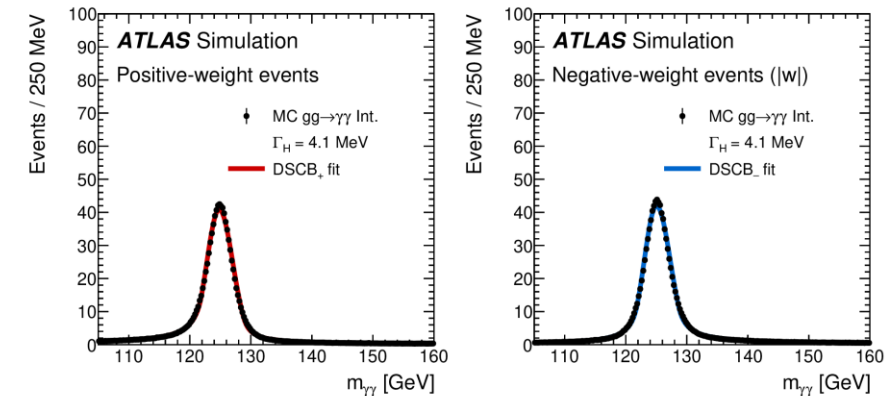
- $H \rightarrow \tau_{had}\tau_{had}$ , fully hadronic top and  $\tau$  decays
- First  $tH$  measurement in the  $H \rightarrow \tau\tau$  channel
- Strategy: multiclass BDT labels  $t\bar{t}H, tH, Z \rightarrow \tau\tau, t\bar{t}$
- First ATLAS use of GNTau  $\tau_{had}$  ID:
  - transformer-based GNN, improved jet rejection & pile-up robustness



# Higgs Width from On-Shell $H \rightarrow \gamma\gamma$ Interference

| Process              | $p_T^{\gamma\gamma} < 30 \text{ GeV}$ | $p_T^{\gamma\gamma} \geq 30 \text{ GeV}$ |
|----------------------|---------------------------------------|------------------------------------------|
| Signal               | 3045                                  | 2527                                     |
| $gg$ -interference   | -60.3                                 | -62.9                                    |
| $qg$ -interference   | +2.4                                  | +6.5                                     |
| Continuum background | $6.7 \times 10^5$                     | $5.1 \times 10^5$                        |

| Uncertainty source                       | $\Delta\Gamma_H \text{ [MeV]}$ |
|------------------------------------------|--------------------------------|
| Theory                                   | 50                             |
| NNLOsv $K$ -factor                       | 49                             |
| Others                                   | 5                              |
| Experimental                             | 53                             |
| $m_H$ (from ATLAS $H \rightarrow ZZ^*$ ) | 43                             |
| Photon energy scale                      | 22                             |
| Photon energy resolution                 | 2                              |
| Others                                   | 7                              |
| Statistical                              | 40                             |
| Total                                    | 77                             |



# CP Structure of $HVV$ interaction: Run 2 Combination

To understand the non-parabolic behavior of the NLL scans, it is helpful to consider the particular cases of  $WH, H \rightarrow b\bar{b}$  and  $H \rightarrow WW^*$ . In these two channels, the impact of the CP-odd operators on the corresponding differential cross-section measurements is parameterized via their impact on their signal strengths  $\mu_p$  (relative to the SM prediction), defined as:

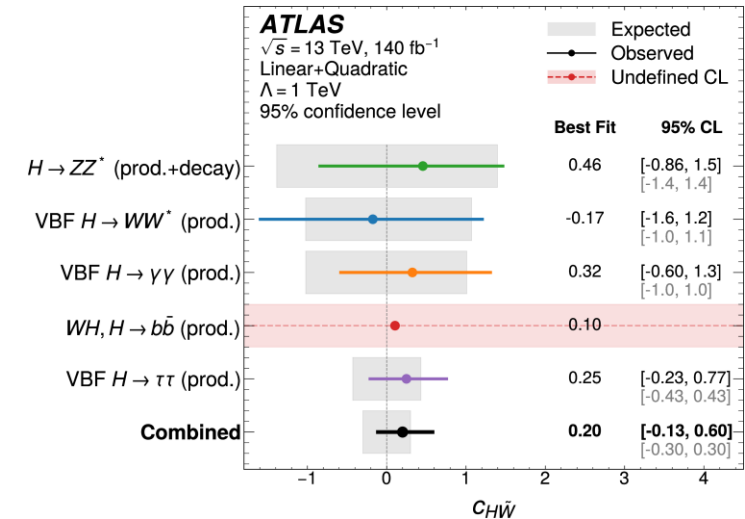
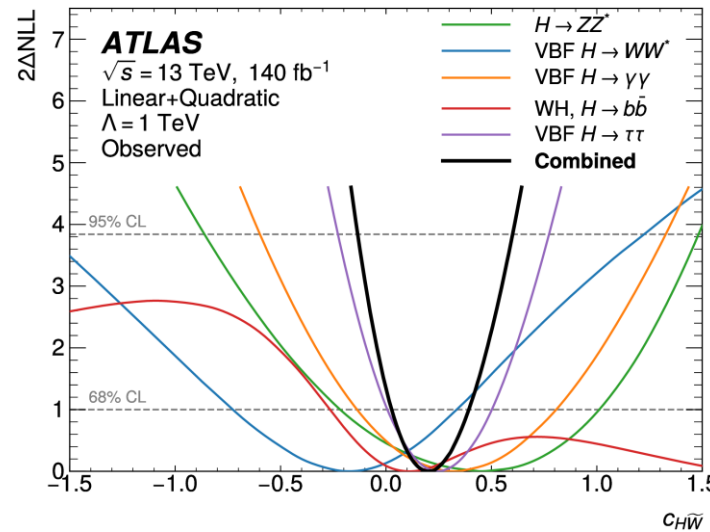
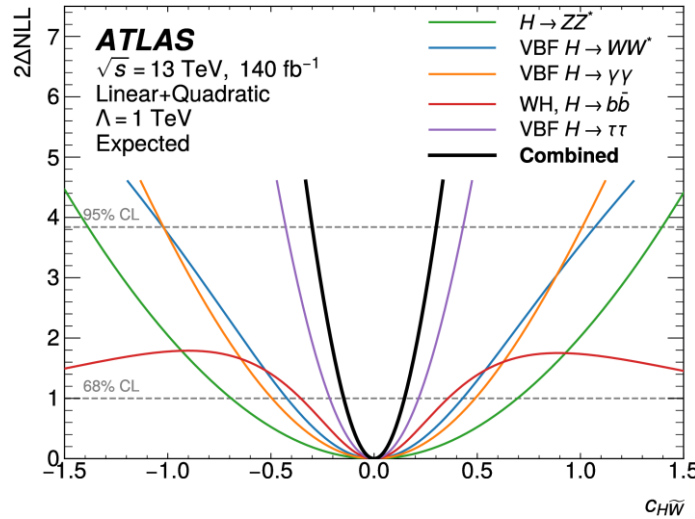
$$\mu_p \rightarrow \mu_p \times \left(1 + \sum_{j=1}^M A_j^p \times c_j + B_j^p \times c_j^2\right), \quad (2)$$

where  $p$  are the STXS particle-level categories,  $A_j^p$  and  $B_j^p$  parameterize the linear and quadratic contributions in STXS region  $p$ , and  $j$  runs through the number  $M$  of CP-odd operators considered. The relative asymmetry across bins of an angular observable can be formulated as  $(\mu_{q^+} - \mu_{q^-})/(\mu_{q^+} + \mu_{q^-})$ , where  $q^\pm$  stands for STXS regions in the same CP-even bin (e.g.,  $p_T^W$ ) and symmetric angular observable bins.

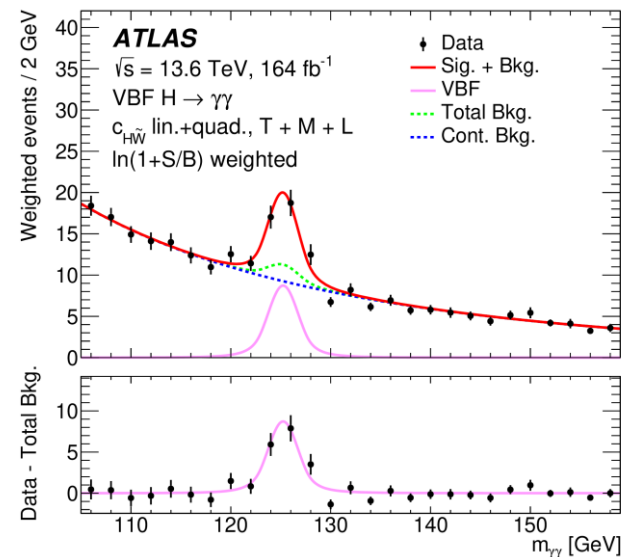
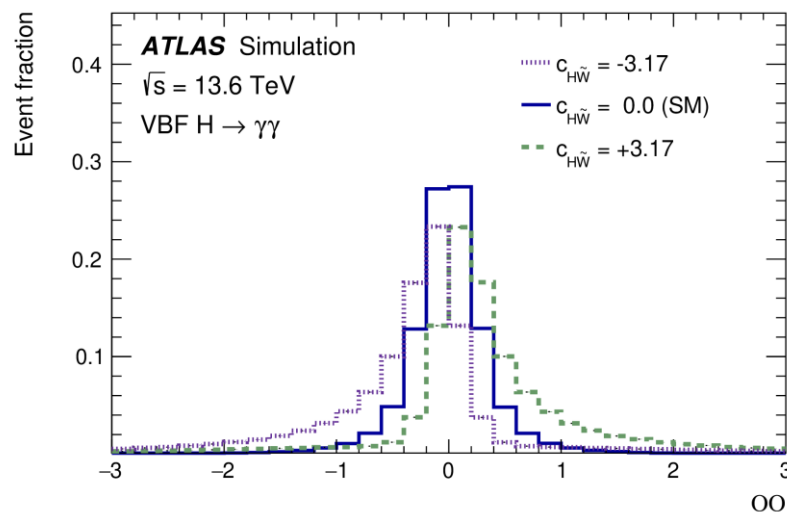
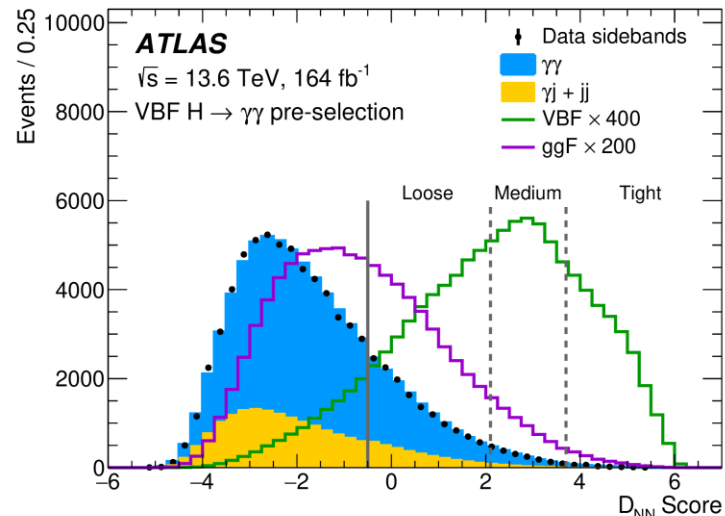
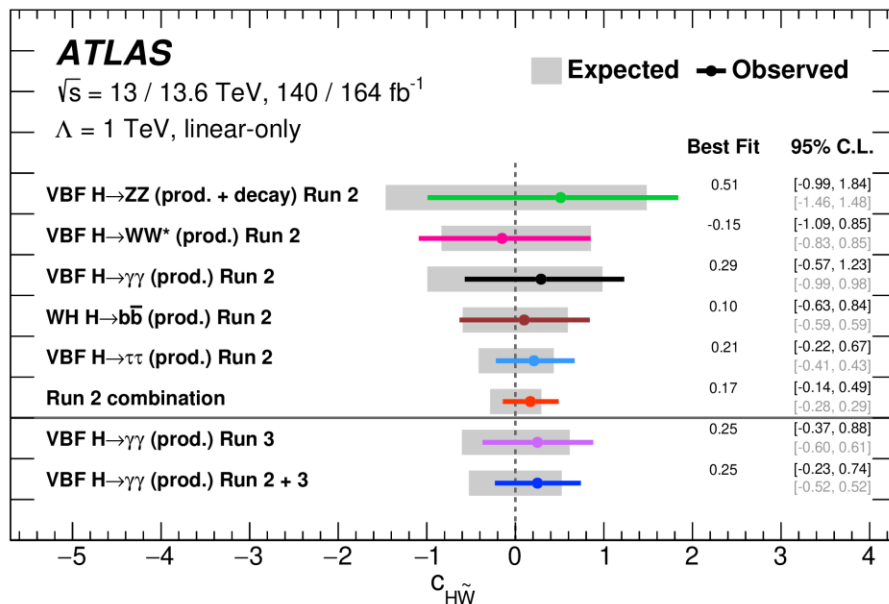
The observed effect in the linear plus quadratic NLL scans is related to how this relative asymmetry depends on the Wilson coefficients. In the linear-only interpretation, this asymmetry grows linearly with  $c_{H\tilde{W}}$  (Eq. 3); however, in the linear plus quadratic scenario this asymmetry grows approximately linearly only for small values of  $c_{H\tilde{W}}$  and is then much reduced (and even inverted) as the absolute value of the coefficient grows (Eq. 4), resulting in the observed NLL behavior.

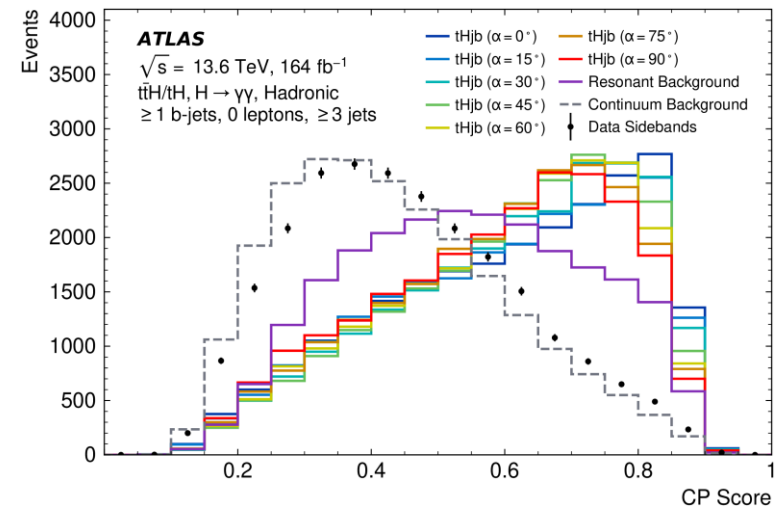
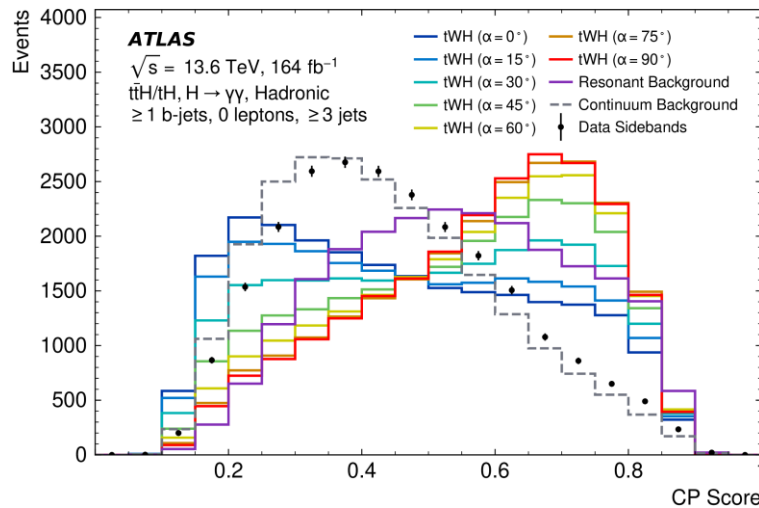
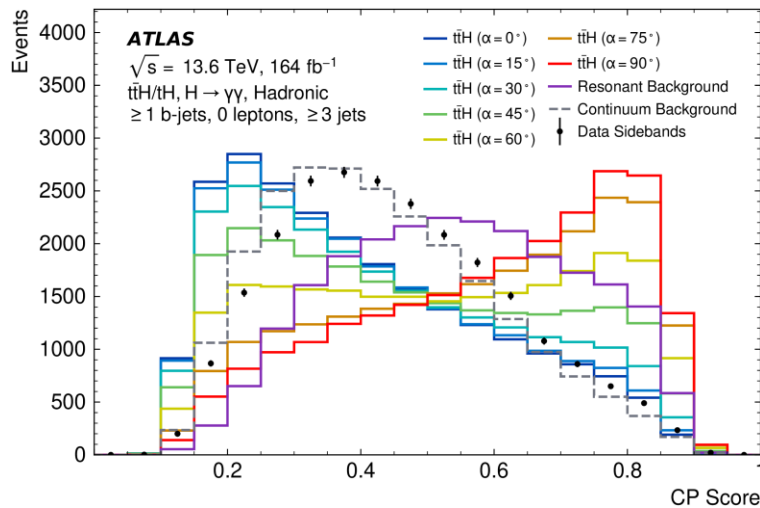
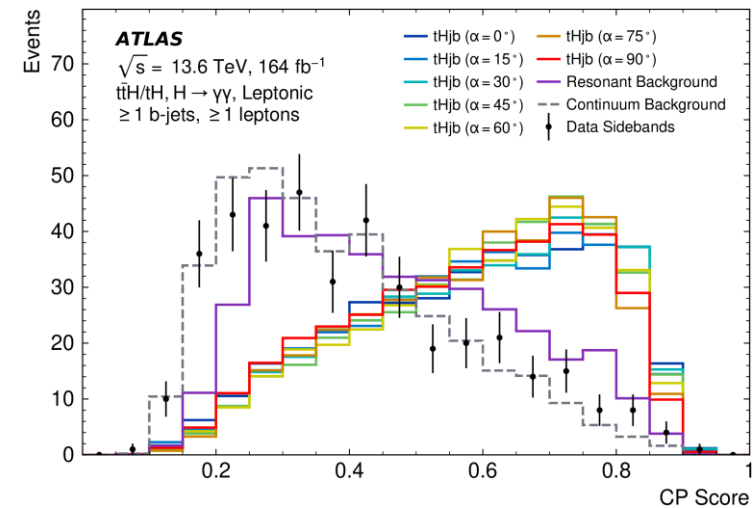
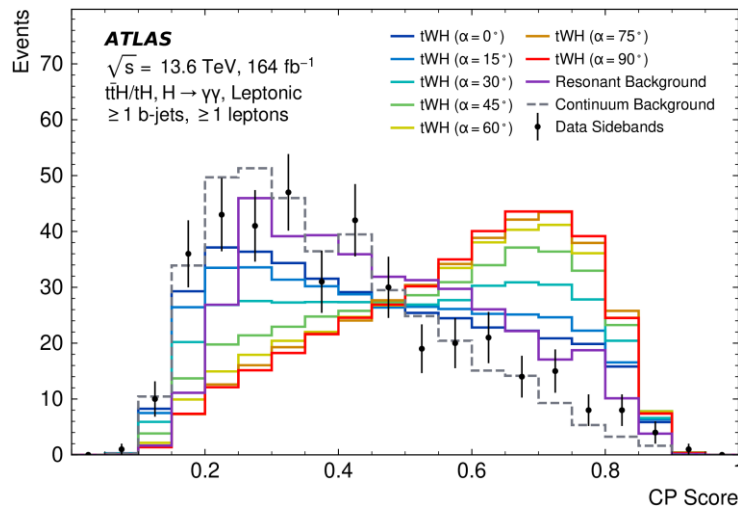
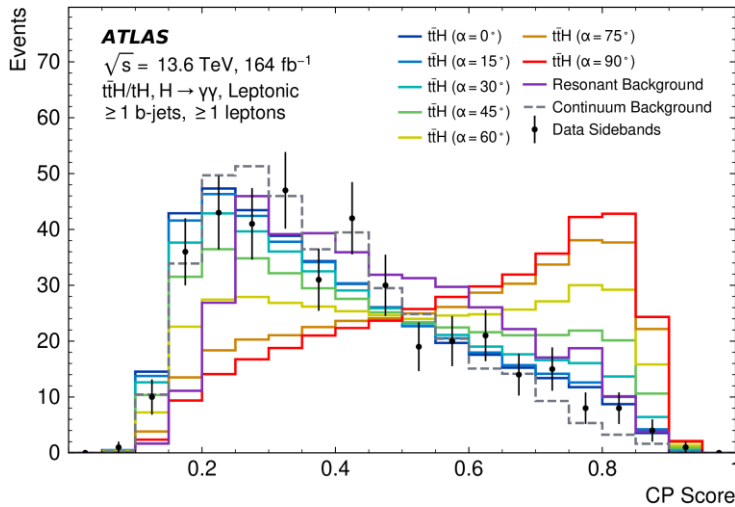
$$\text{Asym}_{p,j}^{\text{linear}} = -A_j^p \times c_j \quad (3)$$

$$\text{Asym}_{p,j}^{\text{linear+quadratic}} = \frac{-A_j^p \times c_j}{1 + B_j^p \times c_j^2} \quad (4)$$



# Partial Run 3 VBF $H \rightarrow \gamma\gamma$





# Run 2 + partial Run 3

## $t\bar{t}H, tH$ production in $H \rightarrow \tau\tau$ Channel

