Studies of the CP properties of the Higgs boson at the ATLAS experiment

Phenomenology Symposium

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Motivation and outline

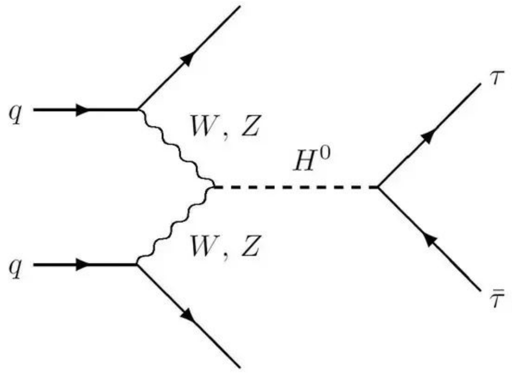
- The Standard Model (SM) predicts the Higgs boson to be a scalar particle ($J^{CP} = 0^{++}$)
- Pure CP-odd Higgs boson has been excluded at 99.9% CL [ATLAS, CMS]
- Presence of a pseudoscalar admixture ($J^{CP} = 0^{+-}$) has not been excluded
  - Any measurement of a CP-odd contribution would be a clear sign of physics beyond the SM
- Looking for potential CP-odd components in the Higgs boson couplings is an important part of the ATLAS physics program

Showing today results from the following analyses (at 13 TeV)

- **Vector boson fusion production (VBF) in $H\to\tau\tau$** ($\mathscr{L}$ = 36.1 /fb, June 2020)
  - Test of CP invariance using the Optimal Observable method, probing **HVV interaction**
- **Production in association with top-quarks in $H\to\gamma\gamma$** ($\mathscr{L}$ = 139 /fb, Aug. 2020)
  - Direct access to top Yukawa coupling, probing **Htt interaction**
- **Production with additional jets in H→WW*** ($\mathscr{L}$ = 36.1 /fb, Nov. 2020)
  - Gluon fusion (ggF): probing effective gluon-Higgs interaction (**Hgg)**
  - VBF: individually probes couplings to longitudinally and transversely polarized vector bosons (**HVV**)

Higgs boson production through VBF in $H\to\tau\tau$

$\mathscr{L}$ = 36.1 /fb at 13 TeV, Phys. Lett. B 805 (2020) 135426

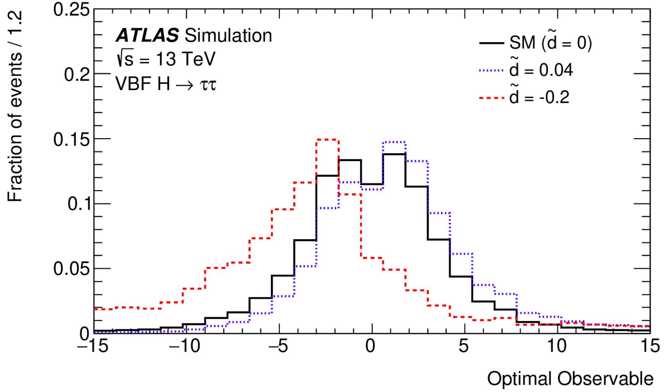


- Targeting leptonic ($\tau\to\ell\nu\nu$) and hadronic τ decays
- Strength of CP violation can be described by a single parameter $\tilde{d}$

$$|\mathcal{M}|^2 = \underbrace{|\mathcal{M}_{\text{SM}}|^2}_{\text{CP-even}} + \underbrace{\tilde{d}\cdot 2\,\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}})}_{\text{CP-odd}} + \underbrace{\tilde{d}^2\cdot|\mathcal{M}_{\text{CP-odd}}|^2}_{\text{CP-even}}$$

- **CP-odd optimal observable** constructed from reconstructed four momenta of Higgs boson and two tagging jets
  - Non-vanishing mean value or an asymmetry would indicate the presence of BSM physics

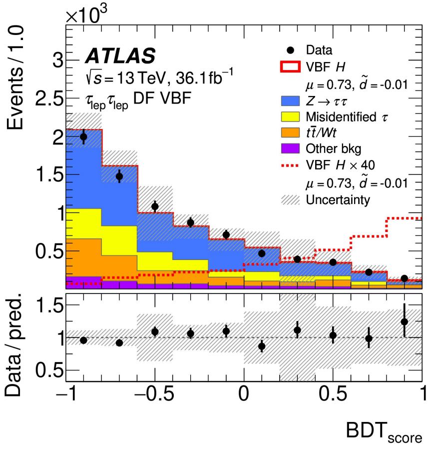
$$\mathcal{O}_{\text{opt}} = \frac{2\,\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2}$$

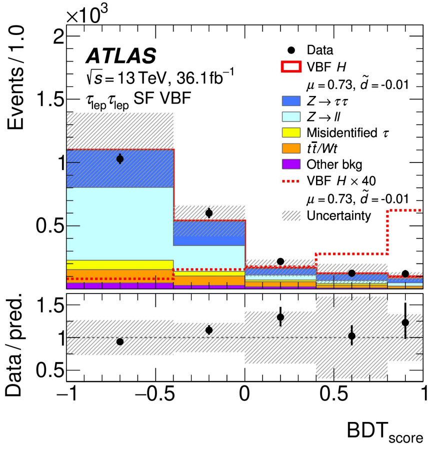


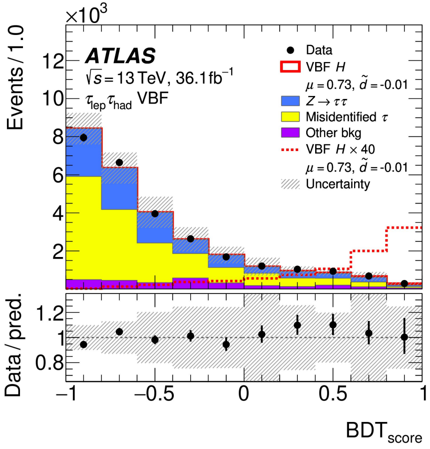
Higgs boson production through VBF in H$\rightarrow\tau\tau$

$\mathscr{L}$ = 36.1 /fb at 13 TeV, [Phys. Lett. B 805 (2020) 135426]

- ≥ 2 jets (VBF topology) and 2 isolated τ-leptons with opposite charge
- **4 analysis channels** based on τ decay
  - $\tau_{lep}\tau_{lep}$ different flavor, $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$: main background from **Z$\rightarrow\tau\tau$** and **misidentified τ**
  - $\tau_{lep}\tau_{lep}$ same flavor: main background **Z$\rightarrow\ell\ell$**
- Selections targeting specific backgrounds
  - **Missing transverse momentum** requirement to reject events without neutrino candidates
  - **B-jet veto** to suppress top-quark backgrounds
- Boosted decision tree (BDT) to further discriminate between VBF signal and backgrounds



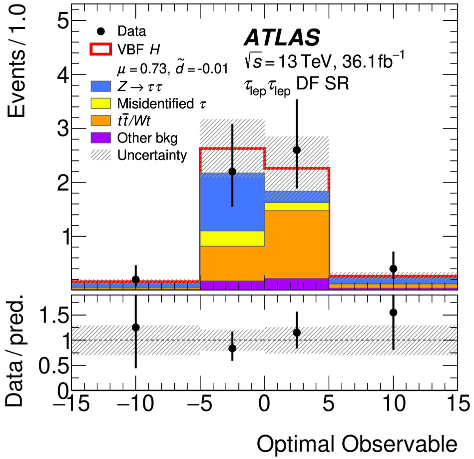




Higgs boson production through VBF in H$\rightarrow\tau\tau$

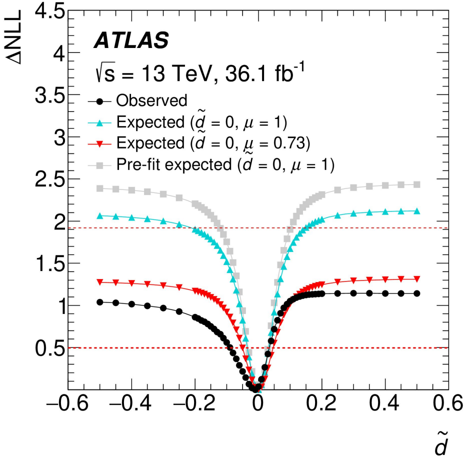
$\mathscr{L}$ = 36.1 /fb at 13 TeV, [Phys. Lett. B 805 (2020) 135426]

- **4 high BDT-score signal regions** (one per channel): fit Optimal Observable
- **4 low BDT-score control regions**: fit reconstructed Higgs mass to constrain the Z$\rightarrow\tau\tau$ normalization
- Dedicated **control regions**: fit event yield to constrain Z$\rightarrow\ell\ell$ and top-quark backgrounds
- Maximum likelihood fit including all signal and control regions
  - **Only shape** information is exploited



Results

- Observed 68% CL of $\tilde{d} \in [-0.090, 0.035]$
- Best-fit signal strength: $\mu = 0.73 \pm 0.47$
- Predicted background distributions for the Optimal Observable are not perfectly symmetrical
- Dominant systematic uncertainties: jet reconstruction (experimental)



Higgs boson production in association with top-quarks in H→$\gamma\gamma$

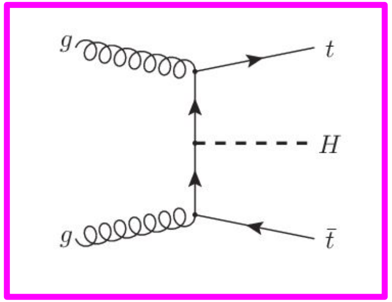
$\mathcal{L}$ = 139 /fb at 13 TeV, Phys. Rev. Lett. 125, 061802

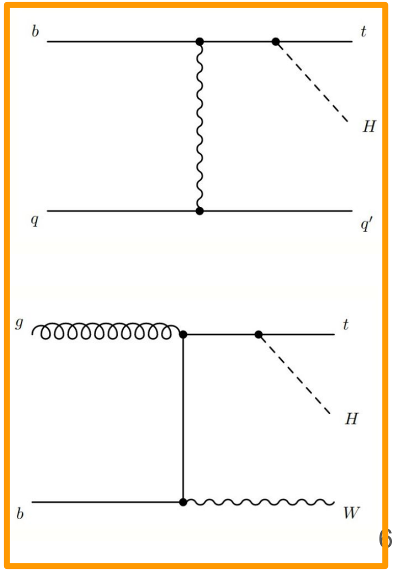
- Higgs boson produced in association with a **top-quark pair (ttH)** or **single top-quark (tH)** and decaying to a pair of photons (H→$\gamma\gamma$)
  - tH rate is particularly sensitive to deviations from SM due to destructive interference between diagrams (but very small cross-section in SM)
- Offers **direct probe** of the top Yukawa coupling
  - **Higgs characterization** model provides EFT framework

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

CP-even (SM) — CP-odd

- Goal is to constrain the 2D phase space given by (κ_t, α)
- **Main background is tt$\gamma\gamma$**: estimated through data-driven approach

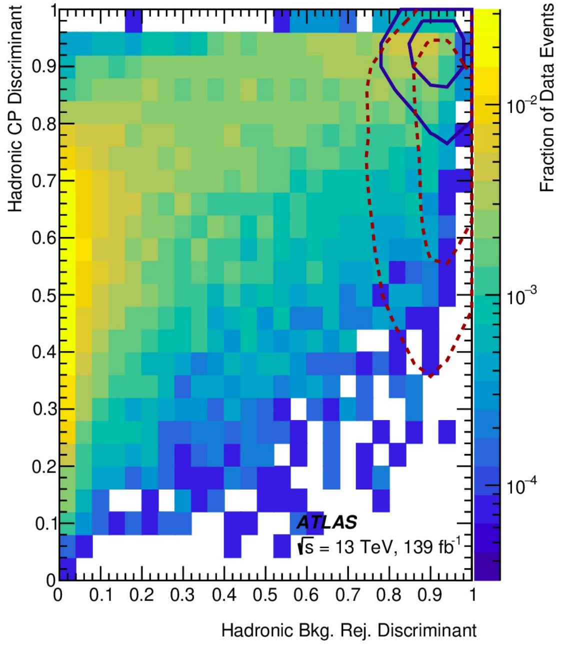


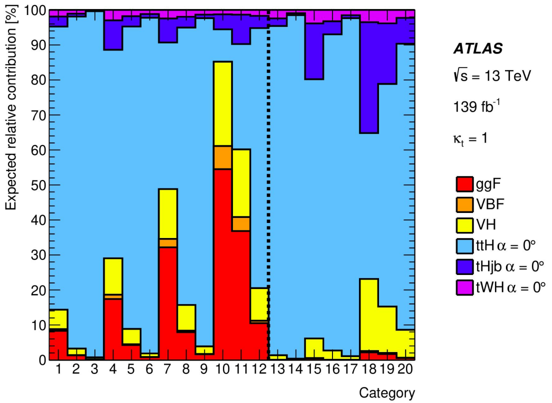


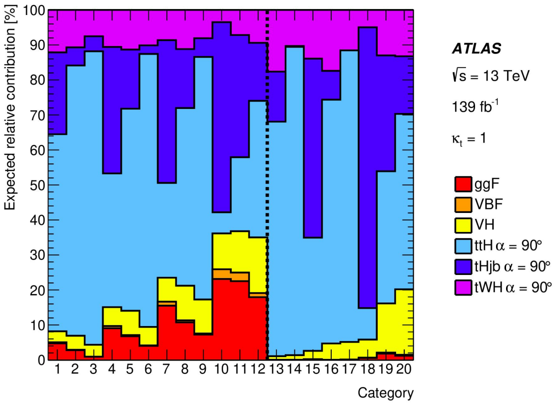
Higgs boson production in association with top-quarks in H$\rightarrow\gamma\gamma$

$\mathcal{L}$ = 139 /fb at 13 TeV, Phys. Rev. Lett. 125, 061802

- Require two isolated photons with p_T>35 (25) GeV
- Two ttH enriched regions target semi-leptonic and hadronic top-decays
- BDT used for top-quark reconstruction
- Events further categorized in **two-dimensional BDT space**
    - Background rejection BDT trained to separate ttH-like events from background
    - CP BDT trained to separate CP-even from CP-odd ttH and tH







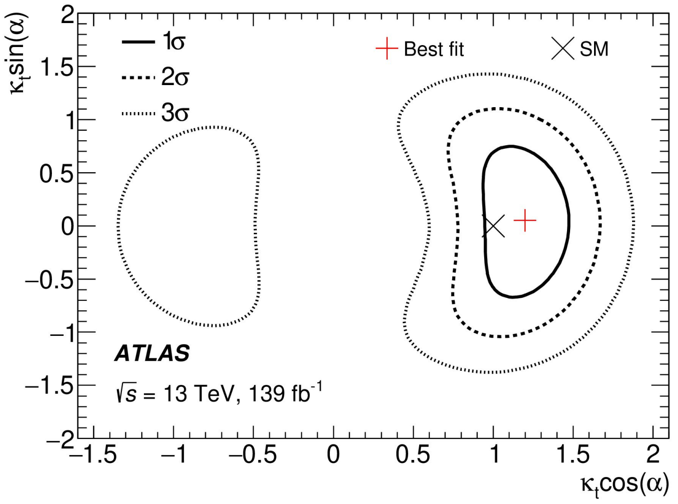
Higgs boson production in association with top-quarks in H→$\gamma\gamma$

$\mathcal{L}$ = 139 /fb at 13 TeV, [Phys. Rev. Lett. 125, 061802]

- Simultaneous maximum-likelihood fit performed to **$m_{\gamma\gamma}$ spectrum** in all regions
  - ttH and tH yields parameterized as a function of α and κ_t
- Parameters of the background model and normalization free to float
- Higgs boson coupling modifiers to photons (κ_γ) and gluons (κ_g) are constrained by the coupling combination analysis (repeated without the ttH and tH inputs)

Results

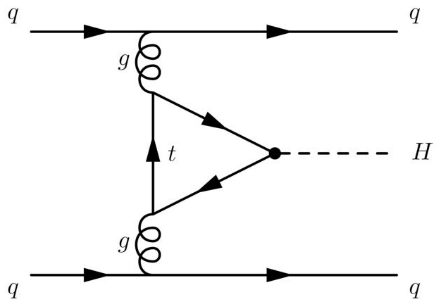
- $|\alpha|$ > 43° is excluded at 95% CL
  - Observed limit does not change if κ_γ and κ_g are parameterized using α and κ_t
- Pure CP-odd coupling (α=90°) is excluded at 3.9σ
- Statistical uncertainty is dominant



Higgs boson properties in H⟶WW*(⟶e$\nu\mu\nu$) + jj

$\mathcal{L}$ = 36.1 /fb at 13 TeV, ATLAS-CONF-2020-055

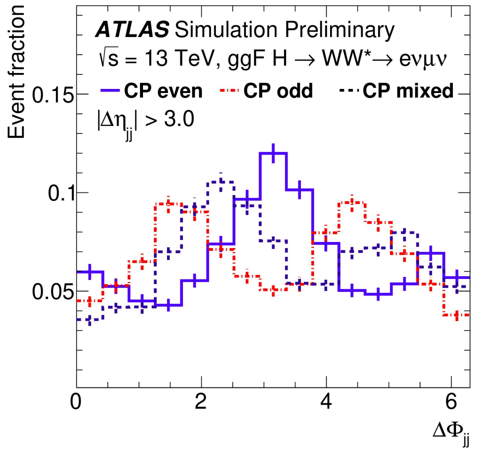
- Higgs boson produced through gluon fusion
- Constrain the properties of the **effective Higgs-gluon interaction**
- **Higgs characterization** model provides EFT framework



$$\mathcal{L}_0^{\text{loop}} = -\frac{1}{4}\left(\kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + \kappa_{Agg} g_{Hgg} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}\right) H$$

CP-even CP-odd

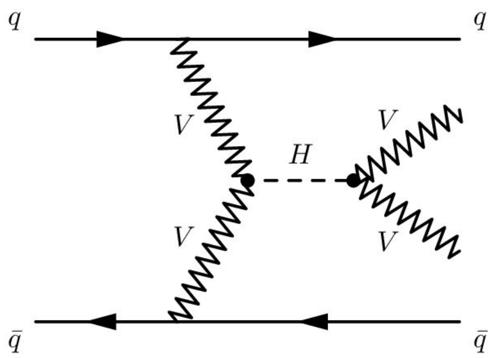
- Goal is to constrain κ_{Hgg} and κ_{Agg}, assuming standard HVV couplings
  - Signed $\Delta\Phi_{jj}$ observable: modulated by interference between CP-even and CP-odd
- Three different samples produced: CP-even, CP-odd and CP-mixed



Higgs boson properties in H→WW*(→$e\nu\mu\nu$) + jj

$\mathcal{L}$ = 36.1 /fb at 13 TeV, [ATLAS-CONF-2020-055]

- Higgs boson produced through vector boson fusion (VBF)
  - HVV vertex present in **production and decay**
- **Individual access** to the Higgs boson couplings to longitudinally and transversely polarized W and Z bosons



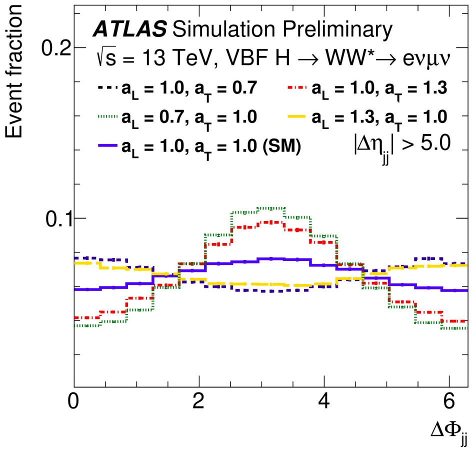
$$a_{\mathrm{L}} = \frac{g_{HV_{\mathrm{L}}V_{\mathrm{L}}}}{g_{HVV}}, \quad a_{\mathrm{T}} = \frac{g_{HV_{\mathrm{T}}V_{\mathrm{T}}}}{g_{HVV}}$$

- Lorentz invariant effective lagrangian given by:

$$\mathcal{L} = \kappa_{VV}\left(\frac{2m_W^2}{v}HW_\mu^+W^{-\mu} + \frac{m_Z^2}{v}HZ_\mu Z^\mu\right) - \frac{\varepsilon_{VV}}{2v}\left(2HW_{\mu\nu}^+W^{-\mu\nu} + HZ_{\mu\nu}Z^{\mu\nu} + HA_{\mu\nu}A^{\mu\nu}\right)$$

SM — BSM

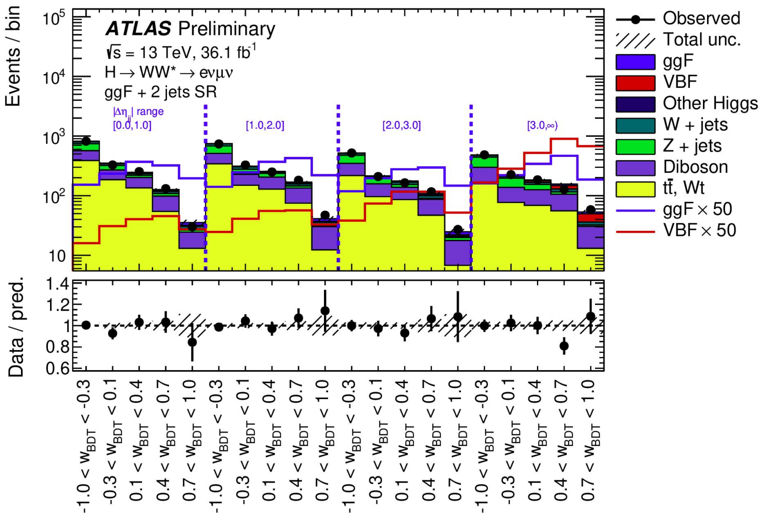
with $\kappa_{VV} \simeq a_{\mathrm{L}}, \quad \varepsilon_{VV} \simeq 0.5 \cdot (a_{\mathrm{T}} - a_{\mathrm{L}})$ (**SM:** $a_L = a_T = 1$)



Higgs boson properties in H$\rightarrow$WW*($\rightarrow e\nu\mu\nu$) + jj

$\mathcal{L}$ = 36.1 /fb at 13 TeV, ATLAS-CONF-2020-055

- **Common preselection** for both studies
  - Two isolated, different-flavour leptons with opposite charge and ≥ 2 jets
- Selections to reject dominant backgrounds: **top-quark, Z$\rightarrow\tau\tau$ and WW**
  - Veto on b-jets and upper limit on di-τ invariant mass (**common**)
  - Minimum p_T and mass of dilepton pair and upper limit on Higgs transverse mass (**ggF+2 jets**)
  - Veto on central jets and leptons within the rapidity gap spanned by the two leading jets (**VBF**)



- Dedicated control regions to constrain the normalization of dominant backgrounds
- BDTs to further separate signal from background

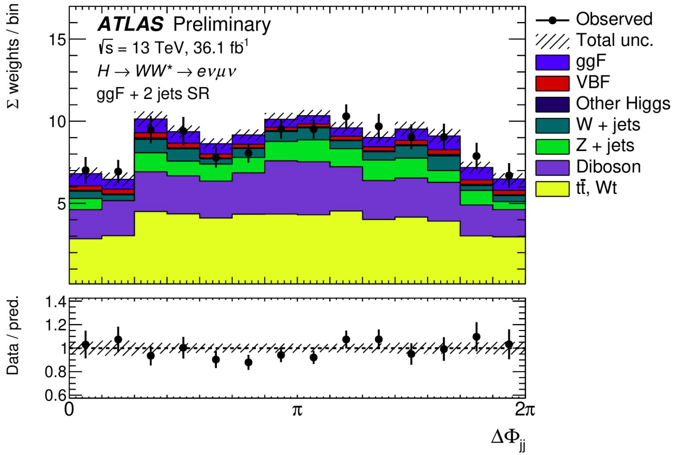
Higgs boson properties in $H \rightarrow WW^*(\rightarrow e\nu\mu\nu)$ + jj

$\mathcal{L}$ = 36.1 /fb at 13 TeV, [ATLAS-CONF-2020-055]

Final CP discriminant: signed $\Delta\Phi_{jj}$

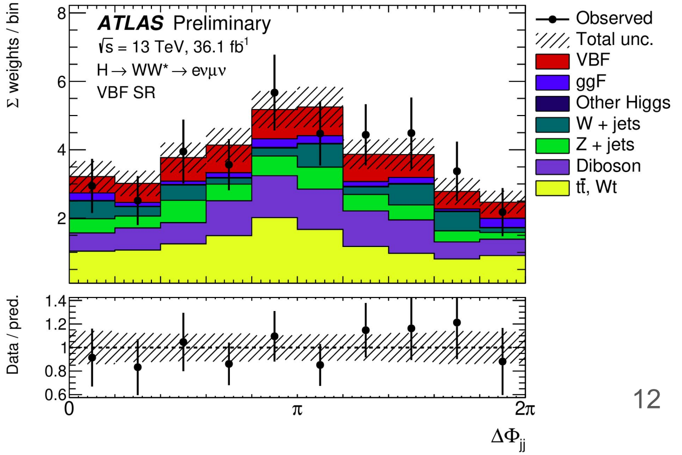
ggF + 2 jets

- **12 categories** split based on BDT score (3) and $|\Delta\eta_{jj}|$: [0.0, 1.0, 2.0, 3.0, ∞]
- Yields in the **top, $Z \rightarrow \tau\tau$ and WW CR's** and in the **low-BDT-score categories (2)** in each $|\Delta\eta_{jj}|$ category are also included
- Free floating normalizations: top-quark, Z+jets and WW+jets



VBF

- **4 categories defined** by the BDT-score
- Yields in the **top and $Z \rightarrow \tau\tau$ CR's** are also included in the fit
- Free floating normalizations: top-quark and Z+jets



Higgs boson properties in H⟶WW*(⟶$e\nu\mu\nu$) + jj

$\mathcal{L}$ = 36.1 /fb at 13 TeV, ATLAS-CONF-2020-055

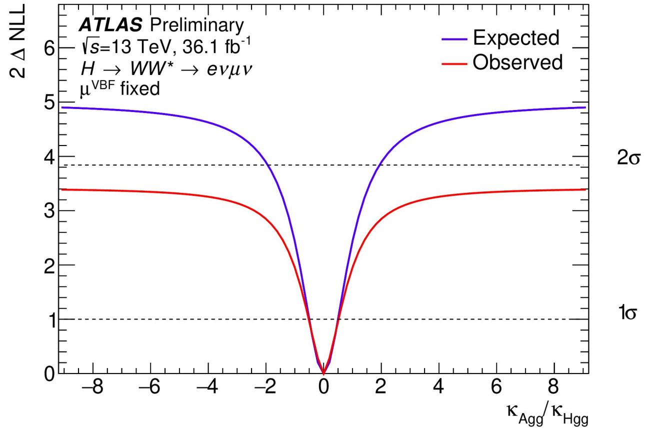
By constraining the signal normalization to model predictions, both **rate and shape** can be exploited, thus increasing sensitivity

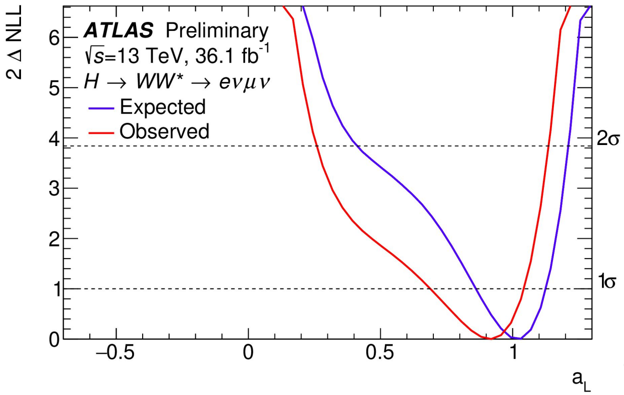
ggF + 2 jets

- Best fit value of $\kappa_{Agg}/\kappa_{Hgg}$ = 0.0 ± 0.4 (stat.) ± 0.3 (sys.)
- Dominant systematic uncertainties: modelling of top-quark background and ggF signal
- If signal normalization is free-floating, data is not sensitive enough to provide 68% CL

VBF

- Best fit values are a_L = 0.90 ± 0.12 (stat.) ± 0.14 (sys.) and a_T = 1.18 ± 0.29 (stat.) ± 0.15 (sys.), with the other fixed to 1
- Results do not change much if the other scale-factor is profiled





Summary

- ATLAS has looked for BSM contributions and set limits on CP anomalous couplings in the Higgs boson interactions with **gluons (Hgg), vector-bosons (HVV) and fermions (Htt)**
    - Exploring multiple final states and production modes
    - Employing experimental techniques ranging from Optimal Observable to multivariate discriminants
    - Including datasets with different luminosities, up to full Run-2 statistics
- So far all measurements are in agreement with the SM expectations
- But still a lot of phase space to explore!
    - **Tighter constraints expected** over the next few years once all analyses are performed using the full Run-2 dataset

- For more information: Higgs boson public results

Backup

Higgs boson production through VBF in H→$\tau\tau$

$\mathcal{L}$ = 36.1 /fb at 13 TeV, Phys. Lett. B 805 (2020) 135426

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}^{+}_{\mu\nu} W^{-\mu\nu}$$

$$\tilde{g}_{HAA} = \frac{g}{2m_W}(\tilde{d}\sin^2\theta_W + \tilde{d}_B\cos^2\theta_W) \qquad \tilde{g}_{HAZ} = \frac{g}{2m_W}\sin 2\theta_W(\tilde{d} - \tilde{d}_B)$$

$$\tilde{g}_{HZZ} = \frac{g}{2m_W}(\tilde{d}\cos^2\theta_W + \tilde{d}_B\sin^2\theta_W) \qquad \tilde{g}_{HWW} = \frac{g}{m_W}\tilde{d},$$

$\tilde{d} = \tilde{d}_B$ leads to: $\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d}$ and $\tilde{g}_{HAZ} = 0$

Higgs boson production through VBF in H$\rightarrow\tau\tau$

$\mathcal{L}$ = 36.1 /fb at 13 TeV, Phys. Lett. B 805 (2020) 135426

$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + \tilde{d} \cdot 2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\text{CP-odd}}|^2$$

$$\mathcal{O}_{\mathrm{opt}} = \frac{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

$$2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}}) = \sum_{i,j,k,l} f_i(x_1)f_j(x_2)2\,\mathrm{Re}((\mathcal{M}^{ij\to klH}_{\mathrm{SM}})^*\mathcal{M}^{ij\to klH}_{\text{CP-odd}})$$

$$|\mathcal{M}_{\mathrm{SM}}|^2 = \sum_{i,j,k,l} f_i(x_1)f_j(x_2)|\mathcal{M}^{ij\to klH}_{\mathrm{SM}}|^2 .$$

with $x_{1,2}^{\mathrm{reco}} = \frac{m_{Hjj}}{\sqrt{s}}\mathrm{e}^{\pm y_{Hjj}}$

For each value of d˜, the value of the matrix elements are calculated by HAWK using the kinematics of the reconstructed particles. Since the flavour of the initial- and final-state partons cannot be determined experimentally, the sum over all possible flavour configurations ij→klH weighted by the PDFs is used

Higgs boson production through VBF in H$\rightarrow\tau\tau$

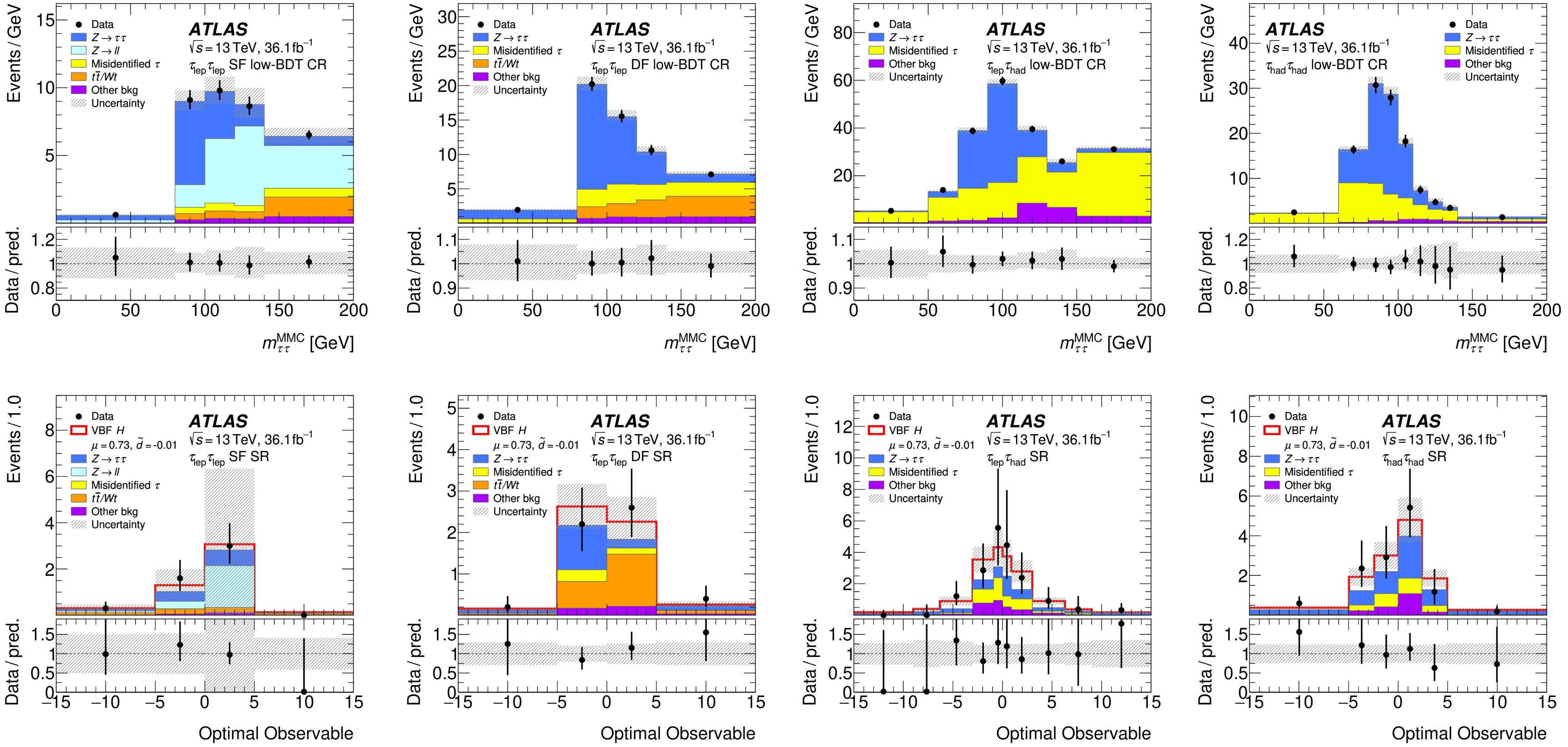
$\mathcal{L}$ = 36.1 /fb at 13 TeV, Phys. Lett. B 805 (2020) 135426

BDT input variables:

- Properties of the Higgs boson which discriminate against all background processes without a Higgs boson: visible mass of di-τ system, transverse momentum of the $\tau\tau$ + missing transverse energy system, **reconstructed Higgs boson mass**
- Properties of the resonant di-τ decay which discriminate against processes with jets that are misidentified as τ-candidates: angular distance, difference in pseudorapidity, difference in azimuth, transverse momentum ratio between MET and τ-candidates, transverse mass of MET and leading τ-candidate, azimuthal centrality of MET
- Properties of the VBF topology: **dijet invariant mass**, total transverse momentum, η**-centralities** of each τ-candidate relative to the pseudorapidity of the two leading jets, transverse momentum of the third leading jet

Higgs boson production through VBF in H→$\tau\tau$

$\mathscr{L}$ = 36.1 /fb at 13 TeV, Phys. Lett. B 805 (2020) 135426



Higgs boson production through VBF in H$\rightarrow\tau\tau$

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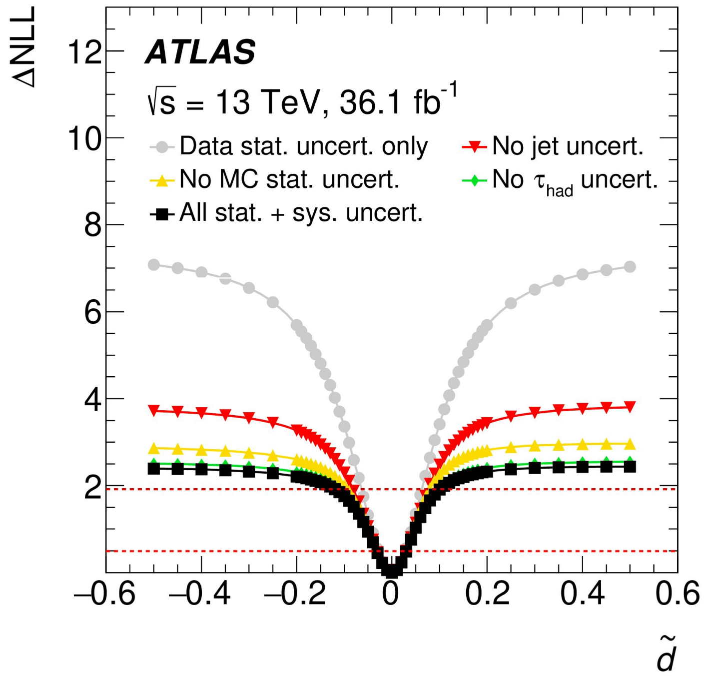
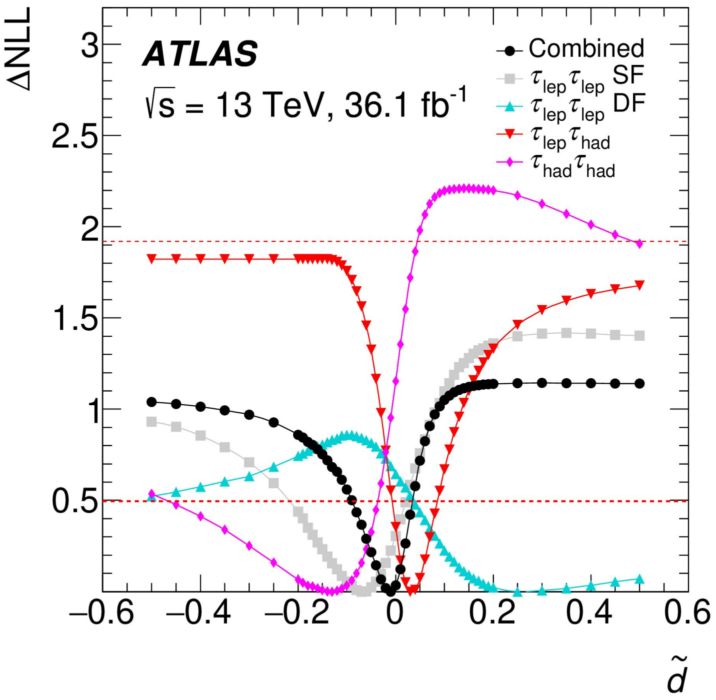




Higgs boson production in association with top-quarks in $H \rightarrow \gamma\gamma$

$\mathscr{L}$ = 139 /fb at 13 TeV, Phys. Rev. Lett. 125, 061802

CP BDT input variables:

- p_T and η of diphoton system
- p_T and η of top-candidates
- top-candidates azimuthal angles calculated relative to the diphoton system
- top-reconstruction BDT scores
- difference in pseudorapidity and azimuth between top-quark candidates
- invariant mass of diphoton and primary top-quark
- invariant mass of two top-quark candidates
- scalar p_T sum of jets (H_T) and MET/$\sqrt{H_T}$
- number of jets and b-tagged jets
- minimum and second-smallest angular differences between a photon and a jet

Higgs boson production in association with top-quarks in H$\rightarrow\gamma\gamma$

$\mathcal{L}$ = 139 /fb at 13 TeV, Phys. Rev. Lett. 125, 061802

Background rejection BDT input variables in leptonic category:

- p_T, η, ϕ and energy of up to four (two) leading jets (leptons)
- magnitude and azimuth of MET
- transverse momentum of each of the two photons divided by the diphoton invariant mass
- η and ϕ of each photon

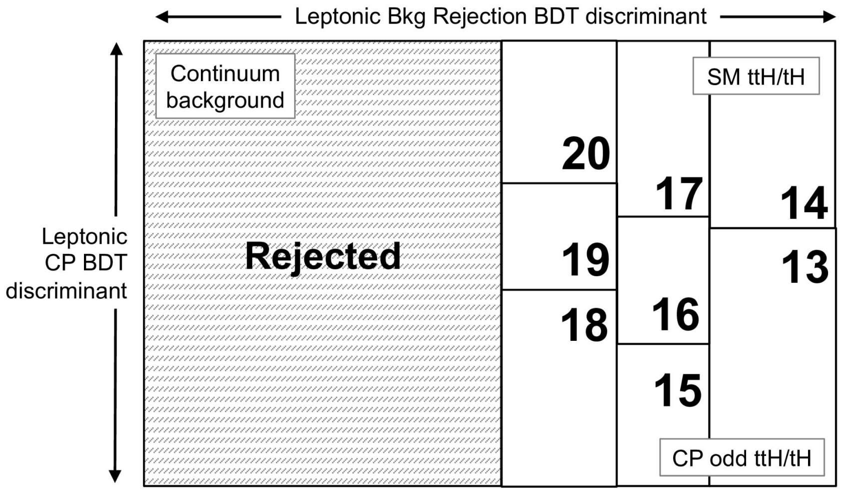
Background rejection BDT input variables in hadronic category:

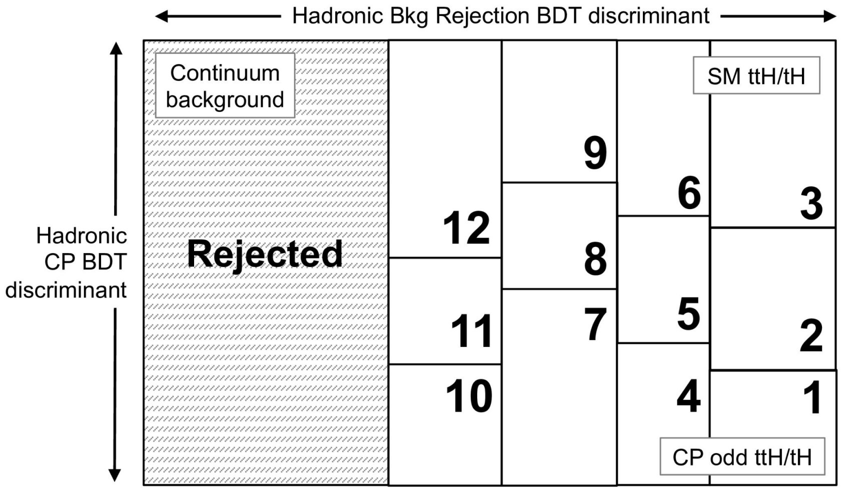
- p_T, η, ϕ, energy and b-tagging decision of up to six leading jets
- missing transverse momentum
- same photon variables as used in leptonic BDT

Higgs boson production in association with top-quarks in H$\rightarrow\gamma\gamma$

$\mathscr{L}$ = 139 /fb at 13 TeV, Phys. Rev. Lett. 125, 061802

- Analysis regions definition in hadronic and leptonic channels

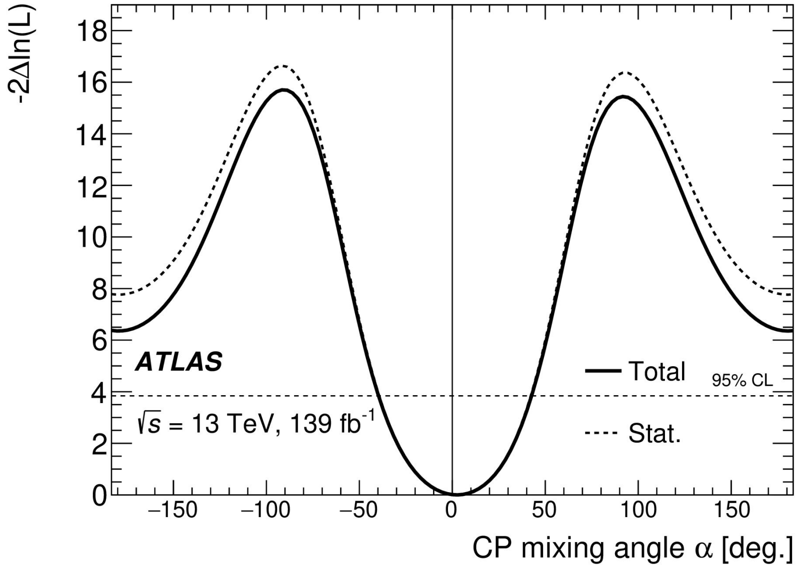




Higgs boson production in association with top-quarks in H→$\gamma\gamma$

$\mathscr{L}$ = 139 /fb at 13 TeV, [Phys. Rev. Lett. 125, 061802]

- 1D likelihood scan on α with κ_t allowed to vary and ggF and H→γγ constrained by Higgs boson coupling combination



Higgs boson properties in H→WW*(→e$\nu\mu\nu$)jj

$\mathcal{L}$ = 36.1 /fb at 13 TeV, ATLAS-CONF-2020-055

BDT input variables in ggF + 2 jets:

- **dilepton invariant mass, transverse momentum and azimuthal angle**
- transverse mass of Higgs boson candidate
- minimal distance between leading and subleading leptons and two tagging jets

BDT input variables in VBF:

- dilepton invariant mass and azimuthal angle
- transverse mass of Higgs boson candidate
- **dijet invariant mass, rapidity difference between two leading jets**
- lepton centrality
- sum of invariant masses of all four possible lepton-jet pairs
- total transverse momentum

Higgs boson properties in H→WW*(→e$\nu\mu\nu$)jj

$\mathscr{L}$ = 36.1 /fb at 13 TeV, ATLAS-CONF-2020-055

$$a_{\mathrm{L}} = \kappa_{VV} + \Delta_{\mathrm{L}}(q_1, q_2)\varepsilon_{VV}\,, \quad a_{\mathrm{T}} = \kappa_{VV} + \Delta_{\mathrm{T}}(q_1, q_2)\varepsilon_{VV}$$

$$\Delta_{\mathrm{L}} = \frac{m_H^2}{2m_W^2}\frac{4q_1^2q_2^2}{m_H^2(m_H^2 - q_1^2 - q_2^2)}\,, \quad \Delta_{\mathrm{T}} = \frac{m_H^2}{2m_W^2}\frac{m_H^2 - q_1^2 - q_2^2}{m_H^2}$$

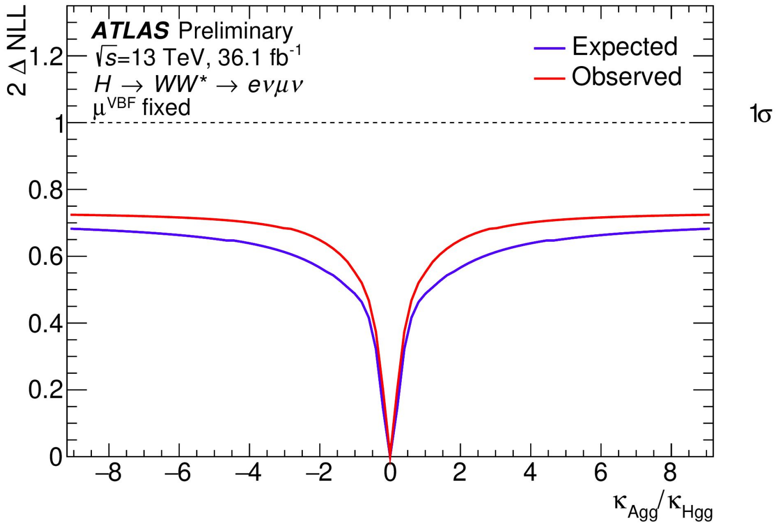
Based on Madgraph5_aMC@NLO simulations, Δ_L(q1, q2) = 0 and Δ_T(q1, q2) = 2 is found to be a good approximation, leading to the mapping used in the analysis:

$$\kappa_{VV} \simeq a_{\mathrm{L}}\,, \quad \varepsilon_{VV} \simeq 0.5 \cdot (a_{\mathrm{T}} - a_{\mathrm{L}})$$

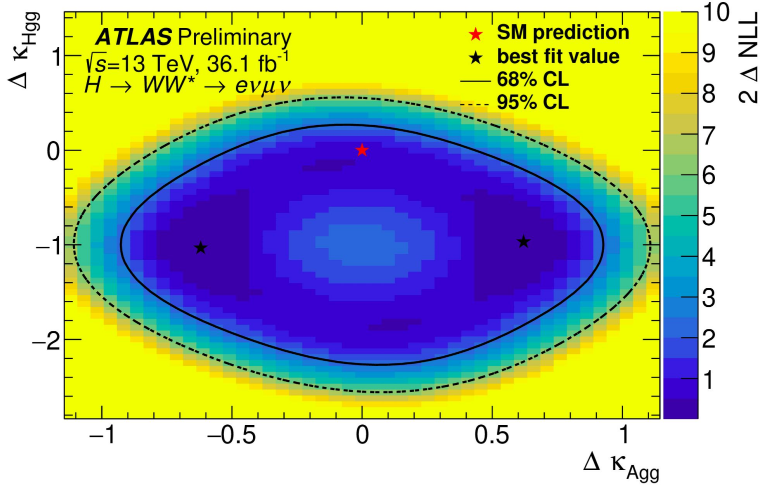
Higgs boson properties in H→WW*(→$e\nu\mu\nu$)jj

$\mathcal{L}$ = 36.1 /fb at 13 TeV, ATLAS-CONF-2020-055

- Expected and observed likelihood curves for scans over $\kappa_{Agg}/\kappa_{Hgg}$ where only the shape is taken into account in the fit



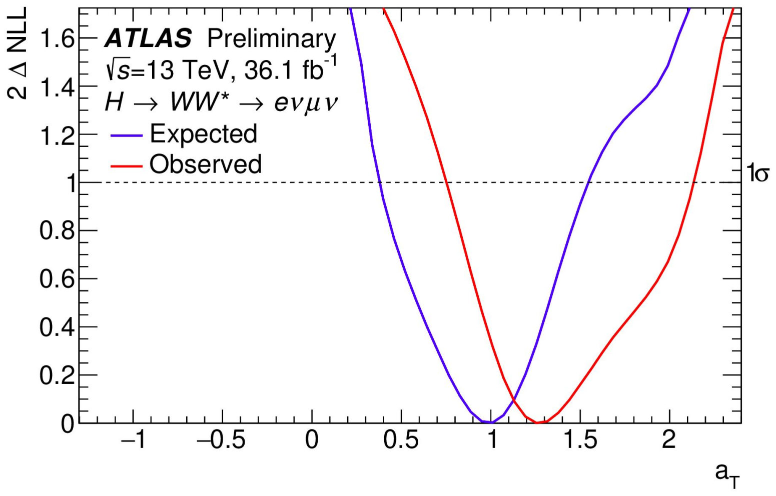
- 68% and 95% CL two-dimensional likelihood contours of the CP-even and CP-odd coupling parameters $\Delta\kappa_{Hgg}$ and $\Delta\kappa_{Agg}$



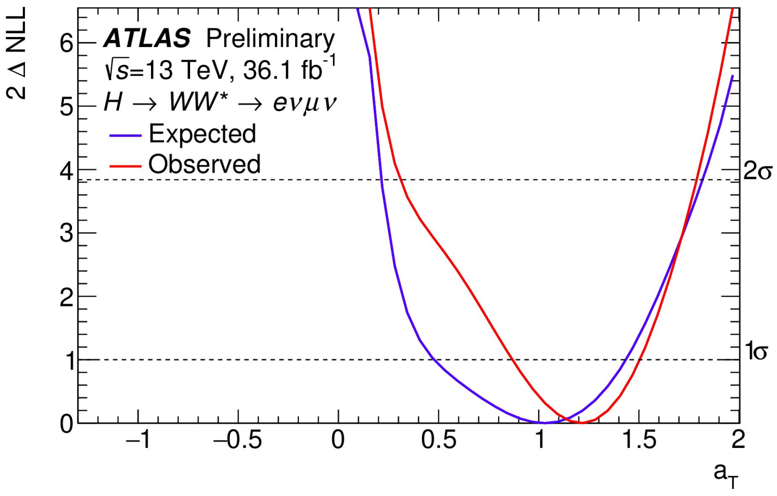
Higgs boson properties in H→WW*(→e$\nu\mu\nu$)jj

$\mathscr{L}$ = 36.1 /fb at 13 TeV, ATLAS-CONF-2020-055

- a_T, shape-only fit with a_L = 1



- a_T shape-rate fit with a_L = 1



Higgs boson properties in H→WW*(→$e\nu\mu\nu$)jj

$\mathcal{L}$ = 36.1 /fb at 13 TeV, ATLAS-CONF-2020-055

- κ_{VV} shape+rate with profiled ε_{VV}
- ε_{VV} shape+rate with profiled κ_{VV}