



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

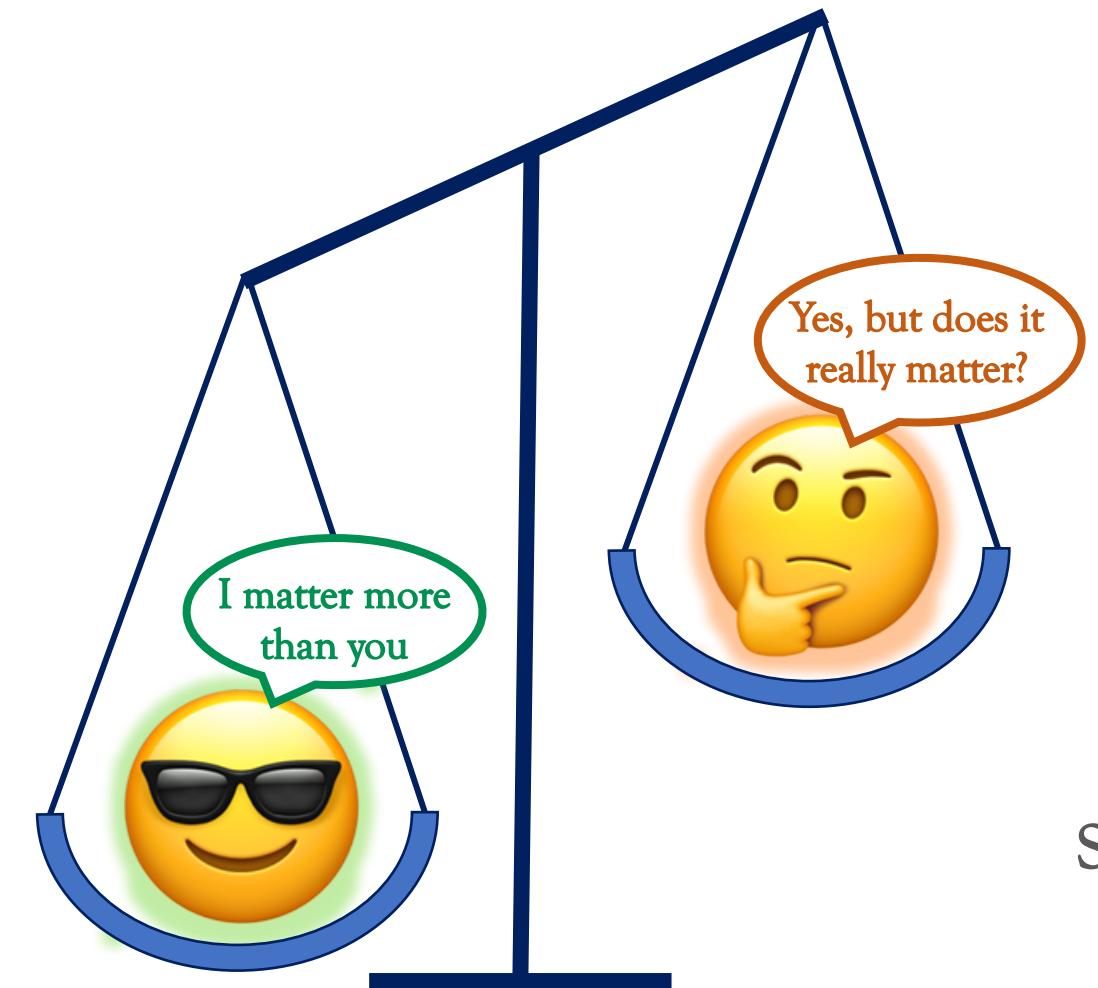
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on behalf of the ATLAS Collaboration

Higgs 2021

20th October 2021

In the Nature CP symmetric?



The asymmetry between the **matter** and **antimatter** content in the universe is one of the **unsolved problems in Physics**



It implies the violation of the charge conjugation and parity symmetry

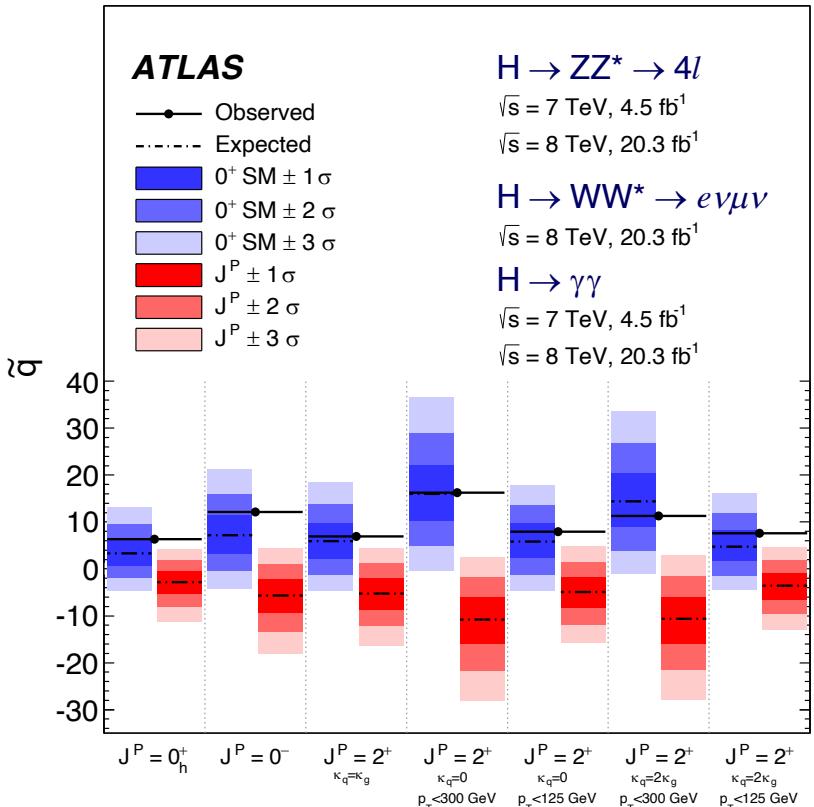


Standard Model can explain just a small level of the CP – violation required
→ Other sources of CP – violation must exist Beyond the Standard Model

CP Violation in the Higgs sector

The Standard Model Higgs boson is a CP-even scalar particle with $J^{CP} = 0^{++}$

- Any sign of CP - Violation → Beyond Standard Model Physics



What has been done during Run1 ($\sqrt{s} = 7\text{--}8$ TeV, 25 fb^{-1})

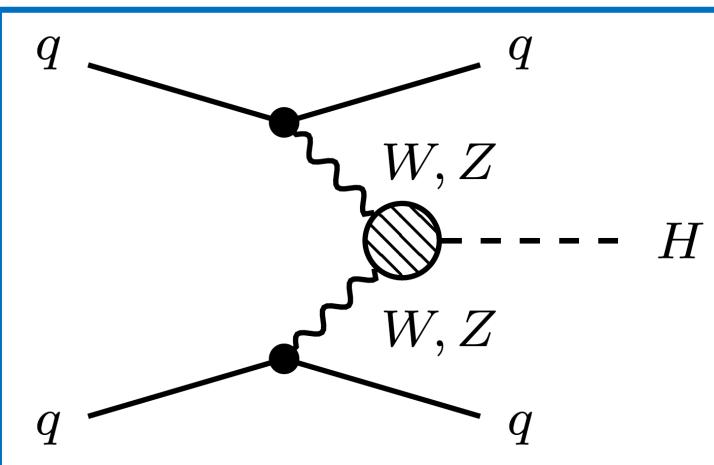
- Analyses aimed to assert that the Higgs boson is CP-even
 - Test of fixed spin and parity hypotheses
 - $J^P = 0^+$ compared with alternative spin-models
 - non-SM hypothesis excluded with at least 99.9 % CL in favor of SM Higgs boson with Spin/Parity 0^{++}
- Investigation of mixing CP-even and CP-odd state looking at the HVV tensor structure
 - Good agreement with SM
 - Approach followed with Run2 ($\sqrt{s} = 13$ TeV, 139 fb^{-1})
 - Probing also other Higgs vertices
 - Focus mainly on the production rather than on the decay

CP structure of the Higgs boson couplings

Searching for signs of CP-violation in the Higgs boson couplings with other SM particles

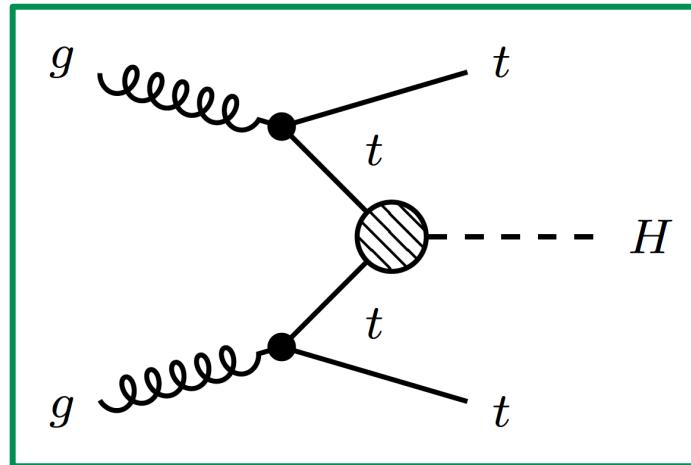
- **Theoretical Framework:** Effective Field Theory (EFT) approaches are commonly used
 - Different models, based on the different assumptions
- **Higgs boson production modes**
 - Existing ATLAS analyses probe different production modes

*HVV coupling in
the VBF production
with $H \rightarrow \tau\tau$*



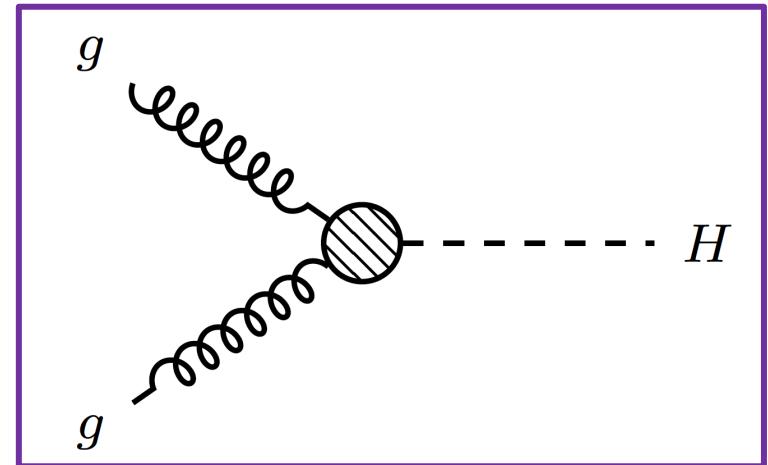
Phys. Lett. B 805 (2020) 135426

*Yukawa coupling with
top quark in the ttH
production with $H \rightarrow \gamma\gamma$*



Phys. Rev. Lett. 125 (2020) 061802

*Effective Higgs-gluon
interaction in the ggH
production with $H \rightarrow W^-W^+$*



arXiv:2109.13808v1

Studies of VBF vertex in $H \rightarrow \tau\tau$

Test of CP invariance in the Higgs couplings with electroweak massive gauge bosons

- Production mode: Vector Boson Fusion (VBF)
 - Assumption: SM Yukawa coupling with taus
- Theoretical framework: EFT in Hawk Basis^{[1][2]}
 - After electroweak symmetry breaking

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

$$\begin{aligned}\tilde{g}_{HAA} &= \frac{g}{2m_W} (\tilde{d} \sin^2 \theta_W + \tilde{d}_B \cos^2 \theta_W) \\ \tilde{g}_{HAZ} &= \frac{g}{2m_W} \sin 2\theta_W (\tilde{d} - \tilde{d}_B) \\ \tilde{g}_{HZZ} &= \frac{g}{2m_W} (\tilde{d} \cos^2 \theta_W + \tilde{d}_B \sin^2 \theta_W) \\ \tilde{g}_{HWW} &= \frac{g}{m_W} \tilde{d},\end{aligned}$$

\tilde{g}_{HVV} , are the couplings of the Higgs boson with the electroweak fields
 → only two of them are independent:
 expressed in terms of dimensionless
 couplings \tilde{d} and \tilde{d}_B describing the
 strength of CP violation

- Assumption: $\tilde{d} = \tilde{d}_B$

- Target: constrain the \tilde{d} parameter

[1] Phys. Rev. Lett. 99 (2007), 161803

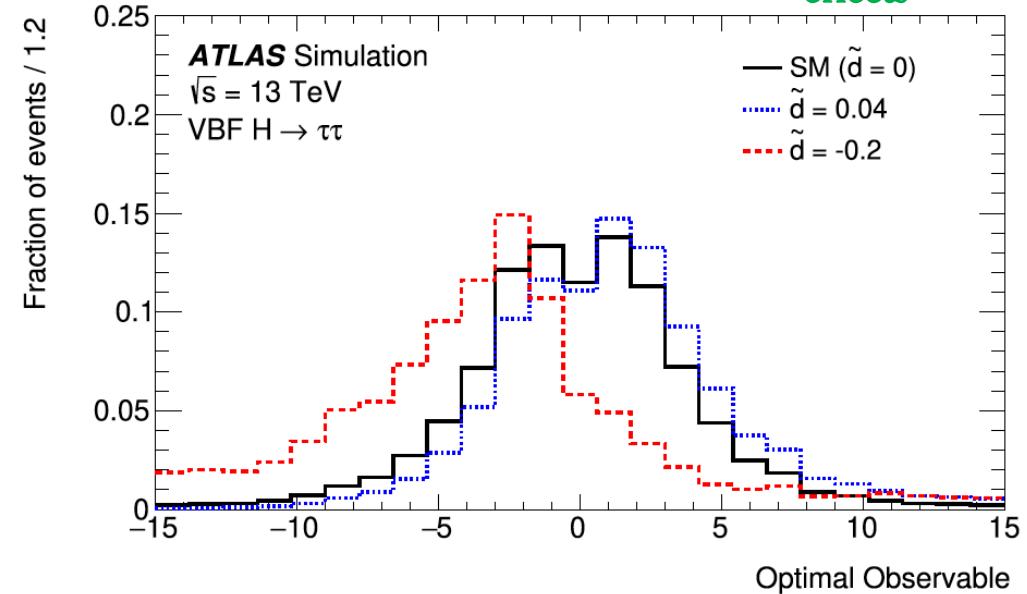
[2] Comput. Phys. Commun. 195 (2015) 161-171

- Sensitive observable: Optimal Observable
 - Combine the kinematic information of the two jets in a single observable

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

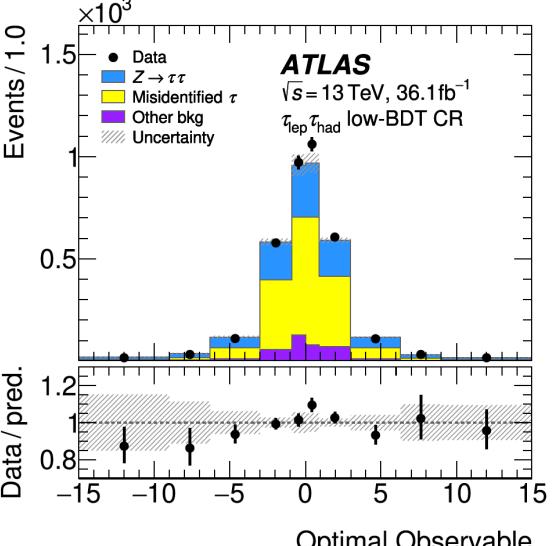
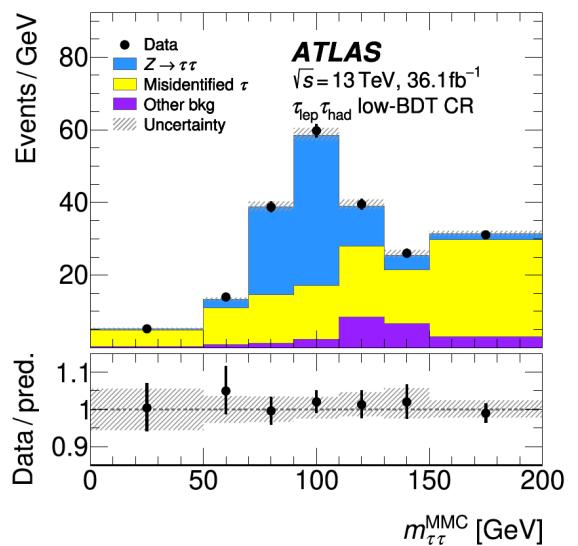
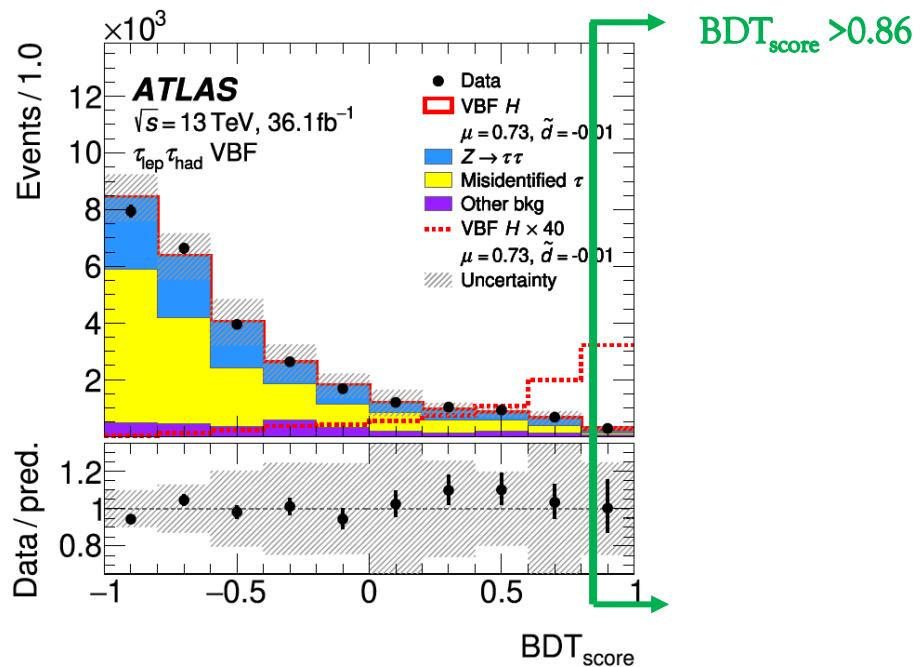
$$\mathcal{O}_{\text{opt}} = \frac{2 \operatorname{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2}$$

Interference term has very high sensitivity to CP effects



Studies of VBF vertex in $H \rightarrow \tau\tau$

- Select events produced by **VBF**
 - Events with at least two jets and $H \rightarrow \tau\tau$ final states:
 - Dileptonic same-flavour ($\tau_{\text{lep}}\tau_{\text{lep}}$ SF)
 - Dileptonic different flavour ($\tau_{\text{lep}}\tau_{\text{lep}}$ DF)
 - Semileptonic ($\tau_{\text{lep}}\tau_{\text{had}}$)
 - Fully hadronic ($\tau_{\text{had}}\tau_{\text{had}}$)
 - BDTs** trained to discriminate **VBF** vs. **background**
 - Different $\text{BDT}_{\text{score}}$ threshold for each channel to define **Signal Region (SR)**
 - Selection requirements on $\text{BDT}_{\text{score}}$ do not bias OO
- Control Region (CR)** defined to constrain the background normalization ($Z \rightarrow \tau\tau$, $Z \rightarrow ll$, top bkg)
 - Inclusion of $m_{\tau\tau}$ distribution in the CR to better constrain the $Z \rightarrow \tau\tau$ contribution
- Perform a **Maximum Likelihood fit** simultaneously on SRs and CRs using OO distribution (and $m_{\tau\tau}$)
- Analysis exploits **only the shape of the OO** (normalization of signal process is not constrained in the fit)

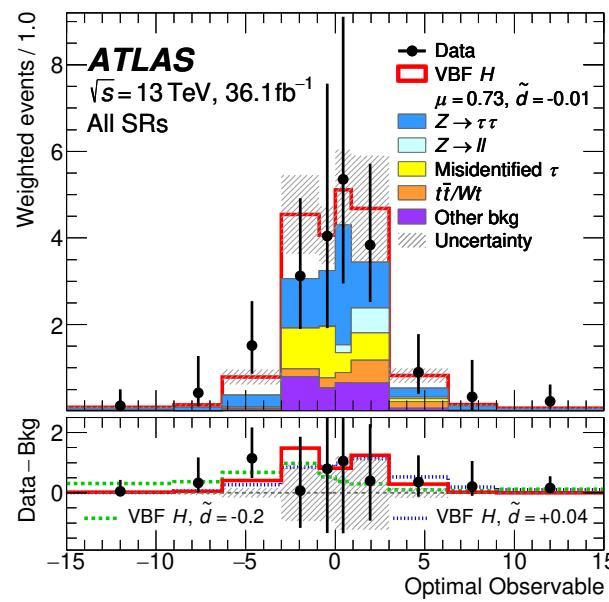


Studies of VBF vertex in $H \rightarrow \tau\tau$

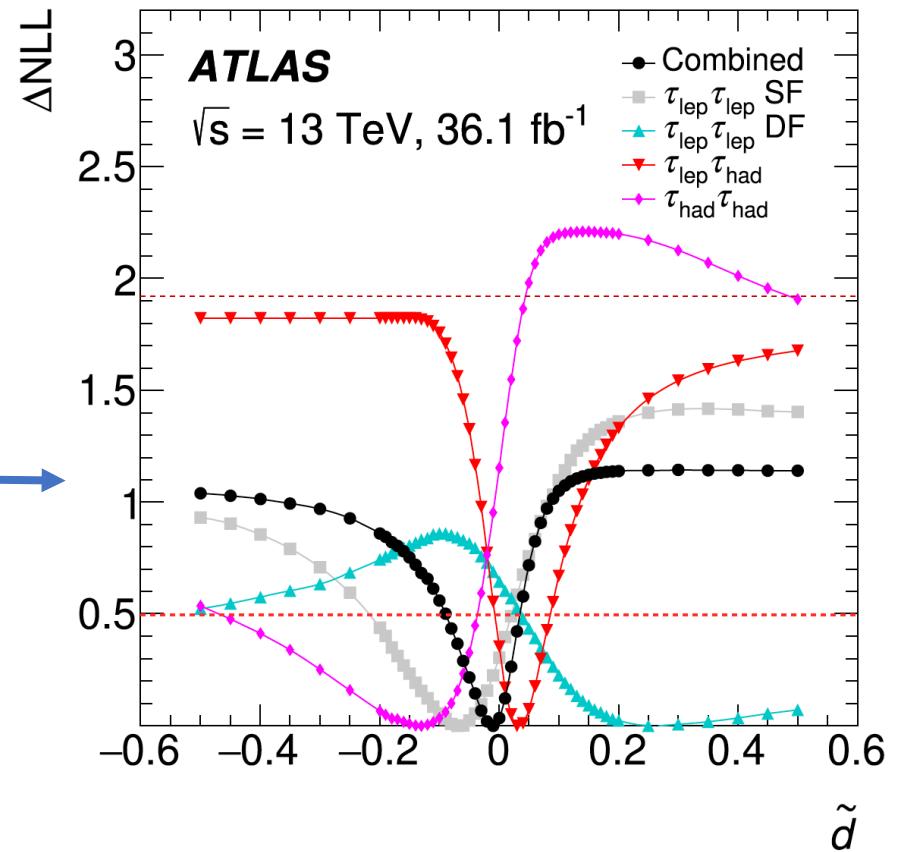
- CP violating effects could result in a deviation from 0 of the Optimal Observable mean value
 - Combining all the individual channel results

Channel	(Optimal observable)
$\tau_{\text{lep}} \tau_{\text{lep}}$ SF	-0.54 ± 0.72
$\tau_{\text{lep}} \tau_{\text{lep}}$ DF	0.71 ± 0.81
$\tau_{\text{lep}} \tau_{\text{had}}$	0.74 ± 0.78
$\tau_{\text{had}} \tau_{\text{had}}$	-1.13 ± 0.65
Combined	-0.19 ± 0.37

Post - fit distribution with smallest \tilde{d} value and the best fit signal strength $\mu = 0.73 \pm 0.47$



Observed results for each analysis channel and combined



- Each channel: considering only the event yields from the other three signal regions
- Signal strength constrained to be positive: fit more stable and insensitive to statistical fluctuation

Observed limit on \tilde{d}
68 % CL = $[-0.090, 0.035]$

Studies of ttH vertex in $H \rightarrow \gamma\gamma$

CP properties of the top Yukawa coupling can be probed directly using Higgs boson production in association with top quarks

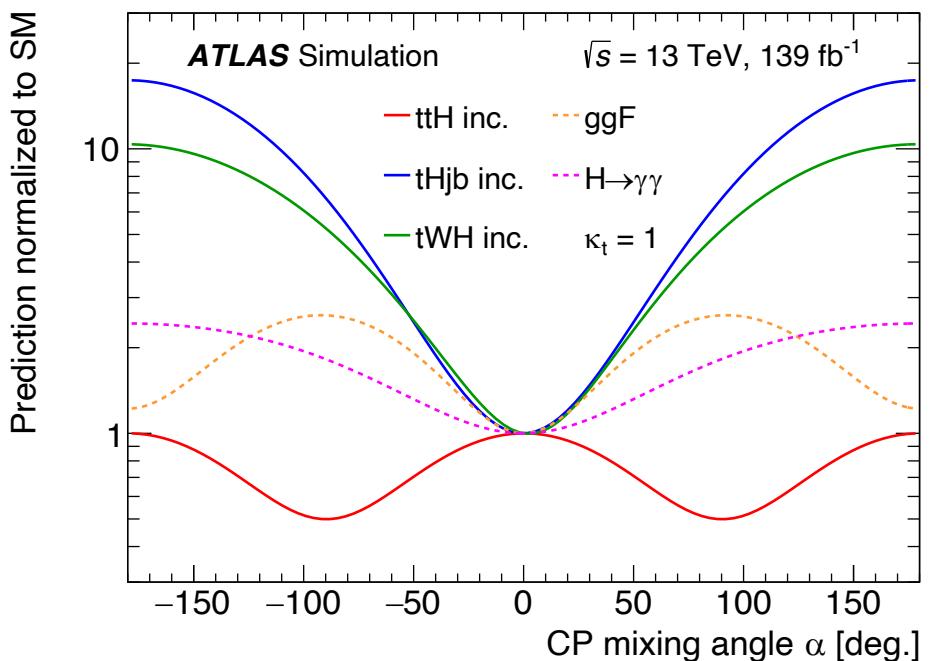
- Production mode: ttH and tH (suppressed)
 - CP mixing in the Yukawa coupling with top can modify the ggF production rate and the $H \rightarrow \gamma\gamma$ decay rate
 - Loop - induced process: modified by other potential new physics

- Theoretical framework: EFT with Higgs Characterization^[1]

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

Top Yukawa coupling CP-mixing angle

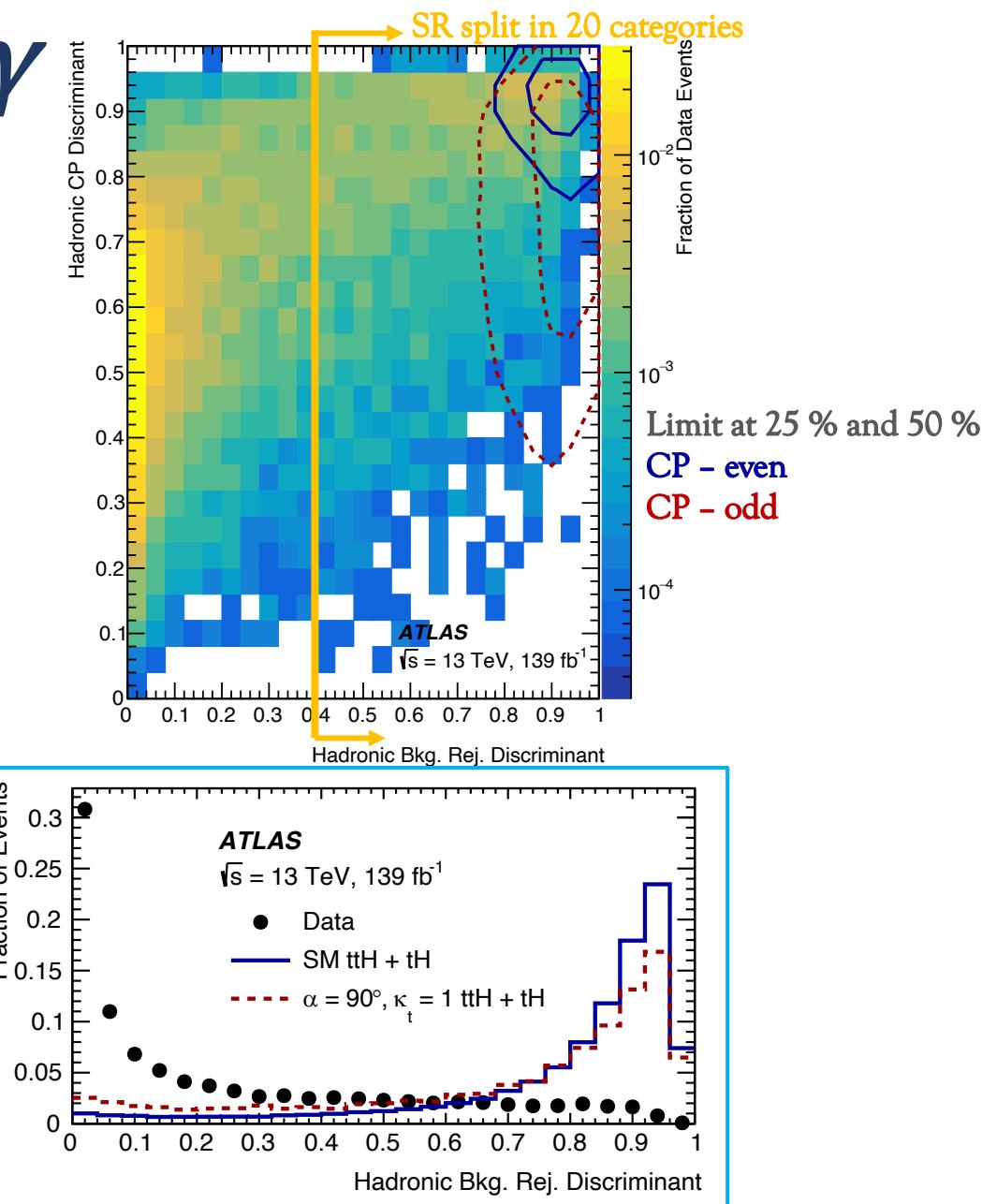
- Target: constrain the CP-mixing angle α



[1] Eur. Phys. J. C 74, 3065, (2014)

Studies of ttH vertex in $H \rightarrow \gamma\gamma$

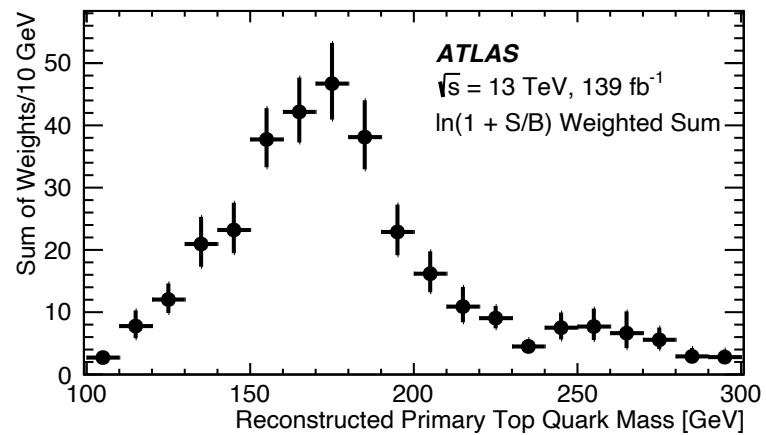
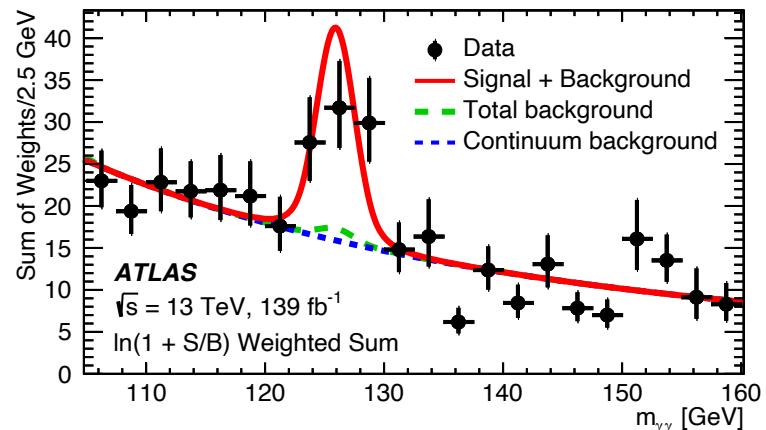
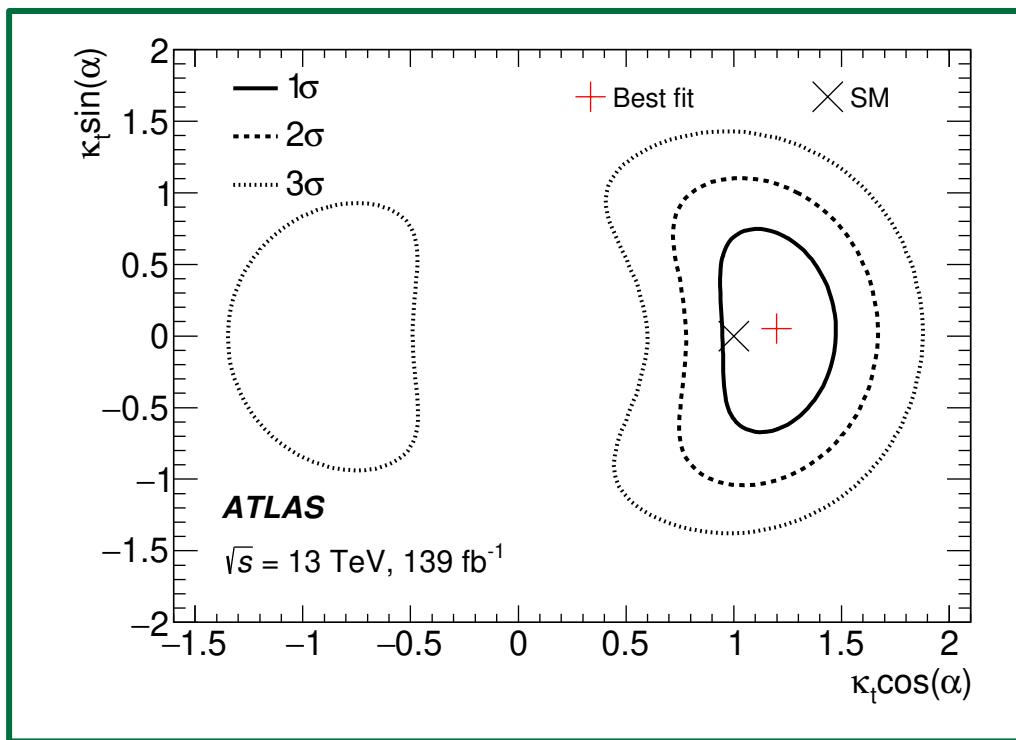
- Selected events in two **ttH-enriched** regions:
 - "Lep" region:** leptonic decay of at least one of the Ws ($t \rightarrow bW$)
 - at least one isolated lepton
 - "Had" region:** hadronic top quark decay
 - at least 2 additional jets
- "Top Reco BDT" used for top quark reconstruction
 - Select the top quark with the highest core
- 2 - Dimensional BDT:
 - Background Rejection BDT:** separate ttH vs. background
 - CP BDT:** separate CP-even vs CP-odd (ttH and tH)
 - Independently trained in the two regions
 - 20 categories: 12 in the "Had" and 8 in the "Lep"
 - Boundaries chosen to optimize the ttH significance
- Simultaneous fit on $m_{\gamma\gamma}$ spectra in all categories
 - Constrain the normalization of the background $t\gamma\gamma$ from the fit
 - Other Higgs boson production are considered as backgrounds



Studies of ttH vertex in $H \rightarrow \gamma\gamma$

- Reconstructed Higgs boson mass and primary top quark masses are reported to ensure a high quality of the selected events
- Measured the rate for ttH: $1.43^{+0.33}_{-0.31}$ (stat) $^{+0.21}_{-0.15}$ (sys) \times SM
 - Yields parametrized in terms of κ_t and α

2D fit of $\kappa_t \cos(\alpha)$ vs $\kappa_t \sin(\alpha)$



→ observed (expected) exclusion on
CP - mixing angle: $|\alpha| > 43$ (56) $^\circ$

Studies of ggH vertex in H \rightarrow WW

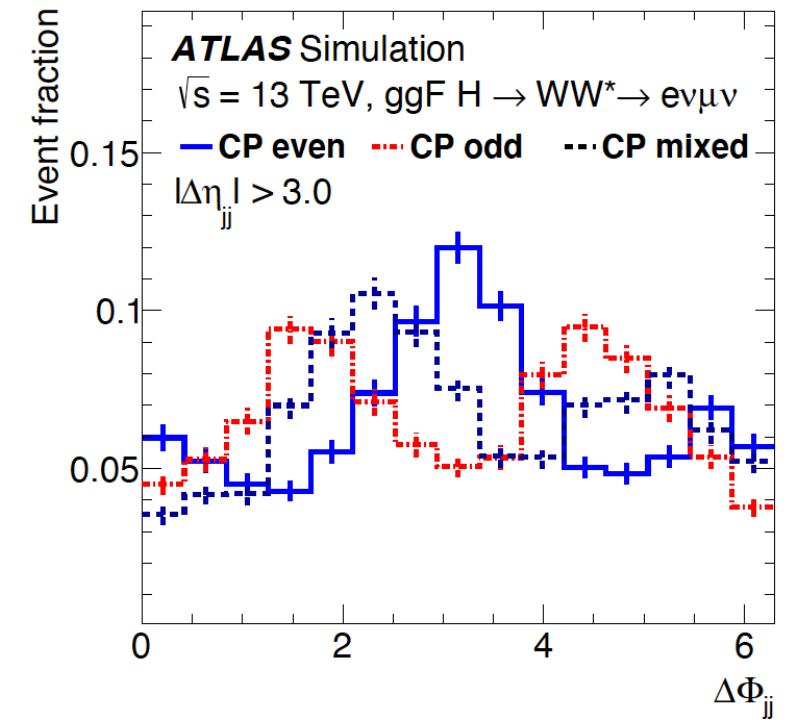
CP properties of the Higgs boson in the effective Higgs – gluon coupling

- **Production mode:** ggH
 - In the large top quark mass limit: the CP structure of the top-quark Yukawa coupling is inherited by the effective Higgs – gluon interaction
 - Assumption: SM-like HVV coupling
- **Theoretical framework:** EFT with **Higgs Characterization**

$$\mathcal{L}_0^{\text{loop}} = -\frac{g_{Hgg}}{4} \left(\kappa_{gg} \cos(\alpha) G_{\mu\nu}^a G^{a,\mu\nu} + \kappa_{gg} \sin(\alpha) G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \right) H$$

Effective coupling CP-mixing angle

- **Target:** constrain the **CP-mixing angle α**
- **Sensitive observable:** **signed- $\Delta\phi_{jj}$**
Signed difference in ϕ of the leading and subleading jets for events with at least two jets
 - Shape sensitive to CP effects



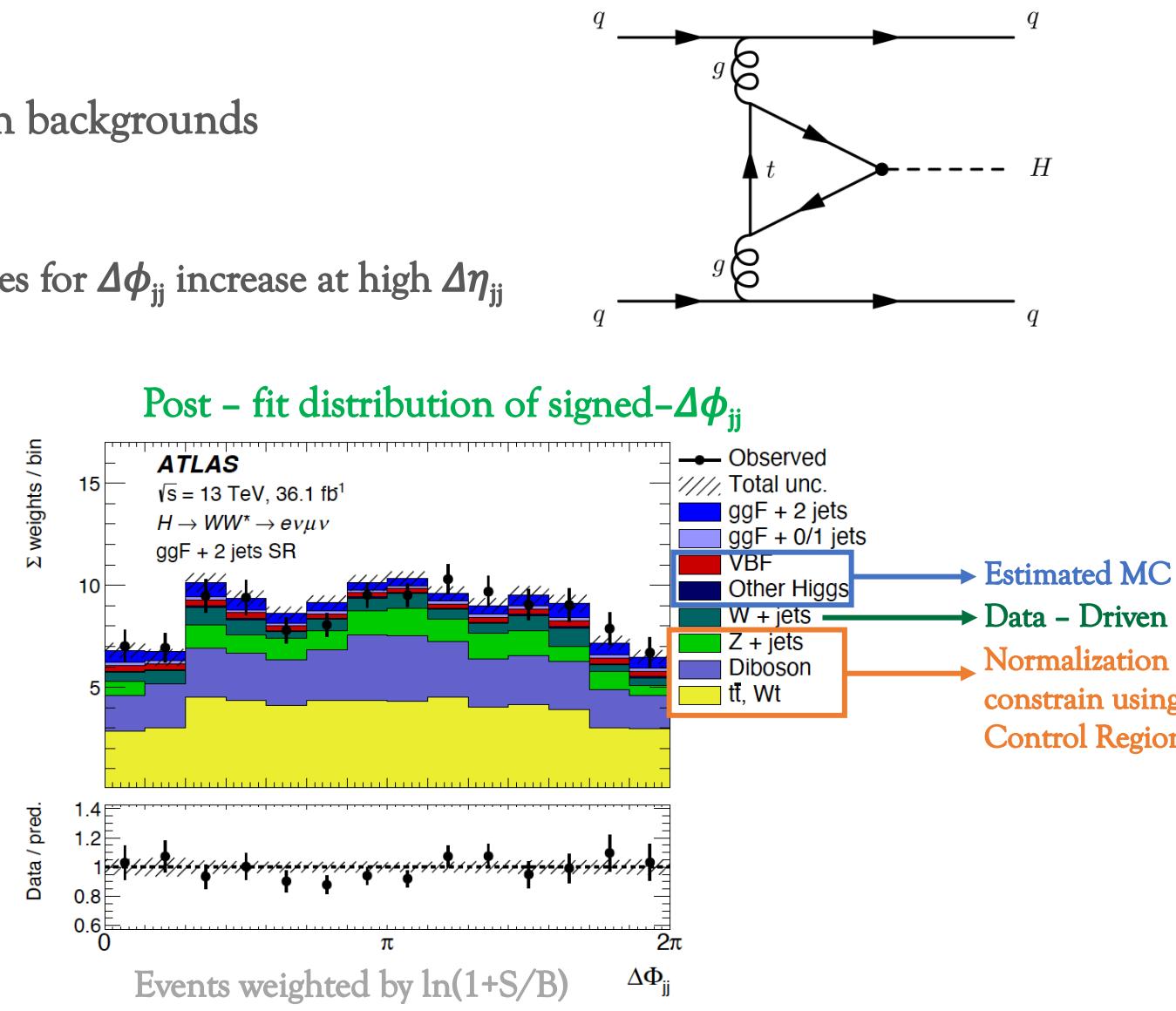
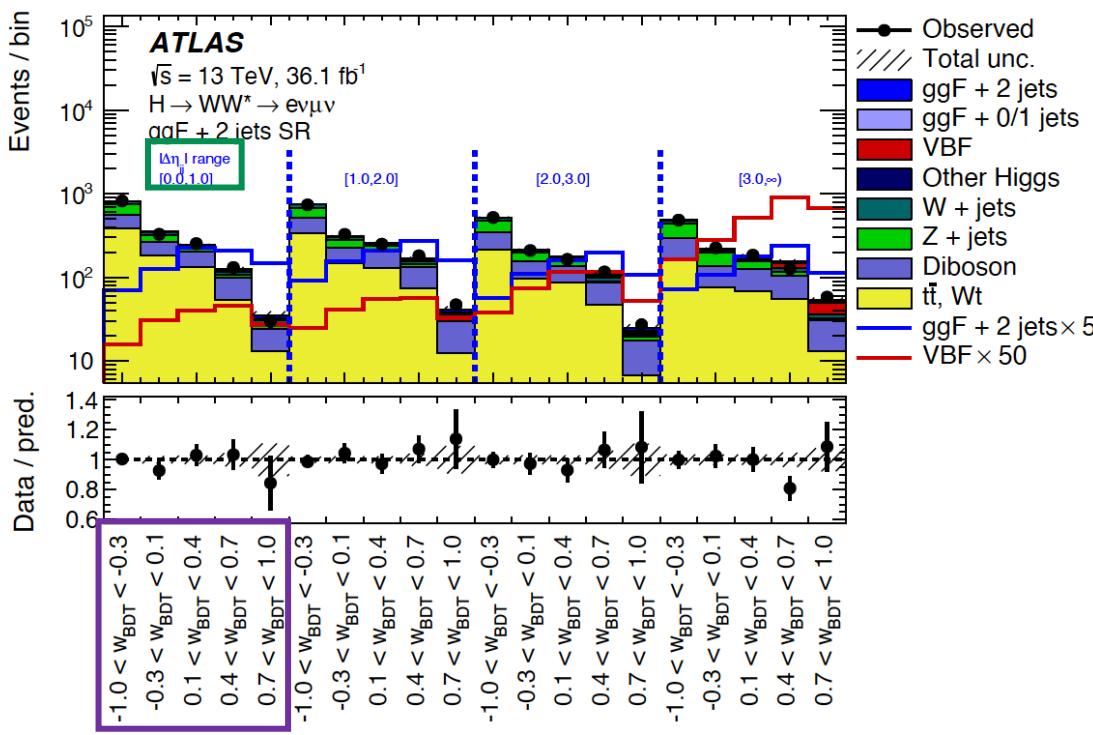
CP – even: $\kappa_{gg} = 1 ; \cos(\alpha) = 1$

CP – odd: $\kappa_{gg} = 1 ; \cos(\alpha) = 0$

CP – mixed: $\kappa_{gg} = 1 ; \cos(\alpha) = 1/\sqrt{2}$

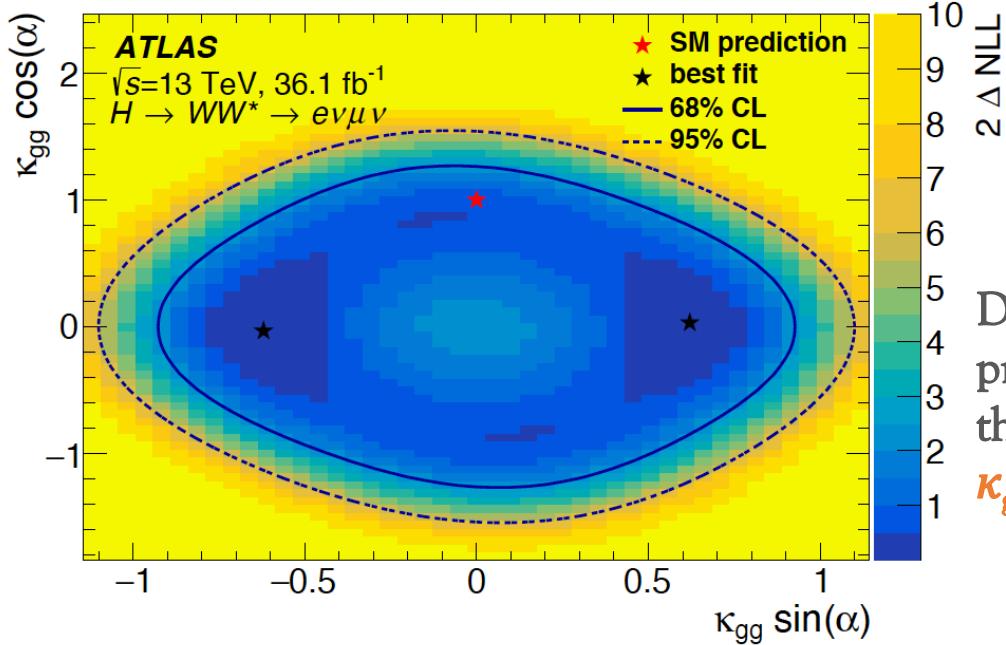
Studies of ggH vertex in H \rightarrow WW

- Select ggF + 2 jets events
- BDT to discriminate H \rightarrow WW signal from the main backgrounds
- Build 12 categories in the 2D space BDT vs $\Delta\eta_{jj}$
 - BDT score split: maximize the signal/bkg ratio
 - $\Delta\eta_{jj}$ split: separation between different CP hypotheses for $\Delta\phi_{jj}$ increase at high $\Delta\eta_{jj}$
 - Perform a fit on signed- $\Delta\phi_{jj}$

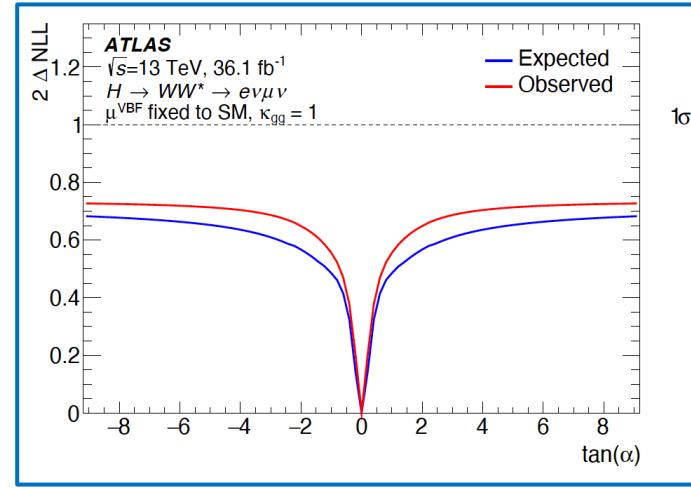


Studies of ggH vertex in H \rightarrow WW

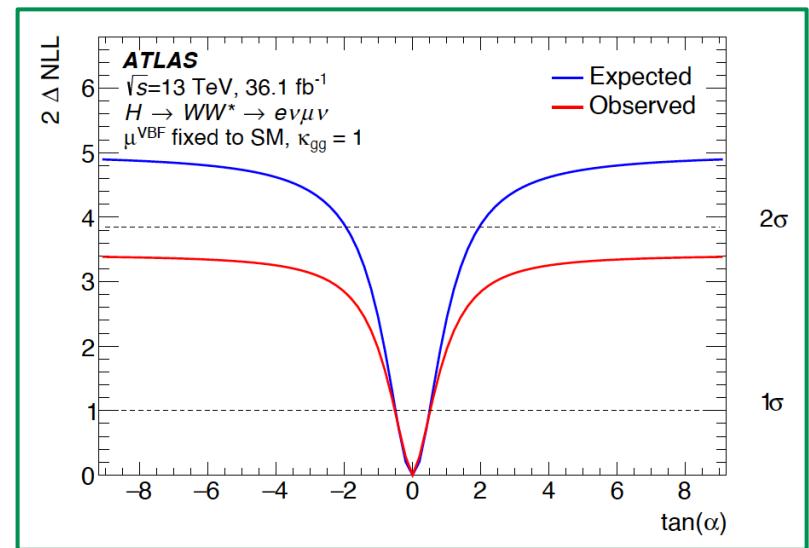
- Perform a fit on signed- $\Delta\phi_{jj}$
 - Two approaches:
 - Exploits only **shape information**: best isolation of CP-dependence
 - Lower sensitivity \rightarrow does not reach 1σ confidence level
 - Both shape and rate** are considered: best sensitivity
 - Observed sensitivity worse than the expected \rightarrow signal strength of the ggF + 2 jets process lower than expected:
- Simultaneous fit** of the coupling strength scale factors



Data consistent with SM prediction within 1σ and the excluded limit
 $\kappa_{gg}\cos(\alpha)$ vs. $\kappa_{gg}\sin(\alpha)$ at 2σ



$$\mu_{\text{ggF+2j}} = 0.5 \pm 0.4 \text{ (stat.)}^{+0.7}_{-0.6} \text{ (syst.)}$$



$$\tan(\alpha) = 0.0 \pm 0.4 \text{ (stat.)} \pm 0.3 \text{ (syst.)}$$

Conclusions

- The study of the CP properties of the Higgs boson is an important field to probe for BSM Physics
 - Searching for sign of CP-violation in the Higgs couplings
- Published results at 13 TeV investigate Higgs couplings with vector boson, top quark and effective gluon-coupling
 - Different theoretical approach can be used to probe different couplings
- No evidence for CP-violation effects up to now

Waiting for new results with full Run 2 dataset!



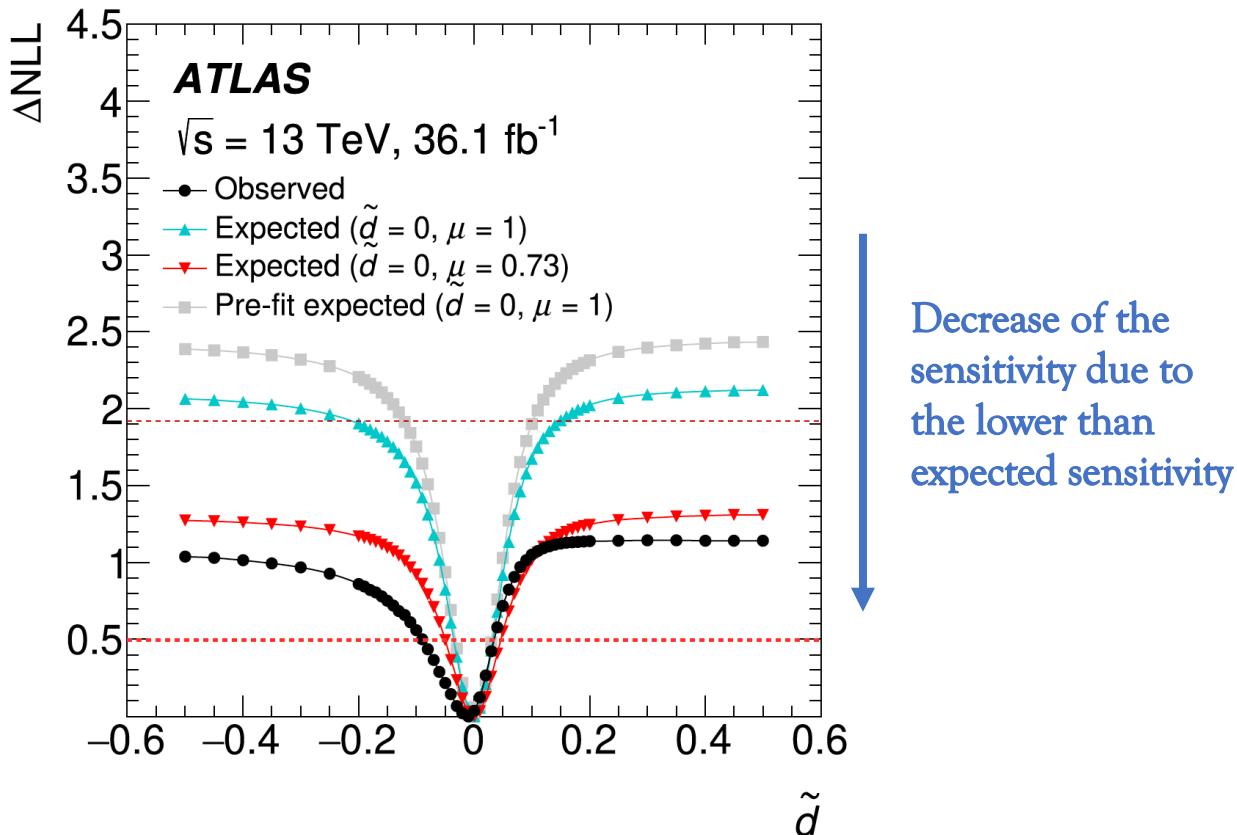
Thanks for the attention!



Backup

Studies of VBF vertex in $H \rightarrow \tau\tau$

Post – fit distribution with smallest \tilde{d} value and
the best fit signal strength $\mu = 0.73 \pm 0.47$



Expected curve run fit twice:

1. Only on CR to constraint bkg normalization and NP
2. Both SR and CR using pseudo-data created from 1.

→ sensitivity consistent with the observed one

Observed is the combination of all the channels

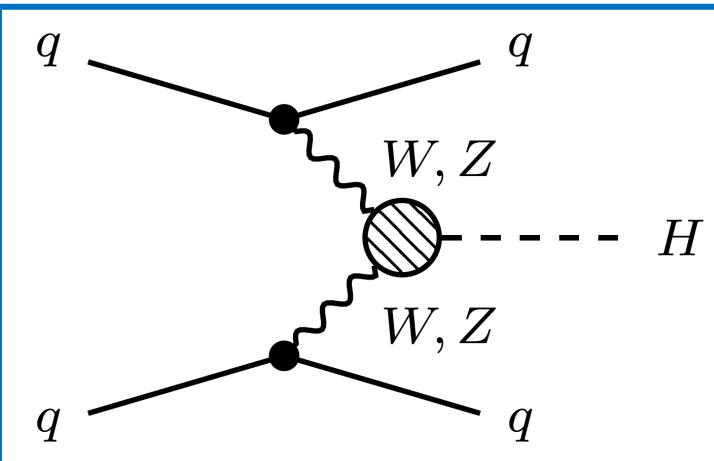
Observed limit on \tilde{d}
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CP properties of the Higgs boson

Searching for signs of CP-violation in the Higgs boson couplings with other SM particles

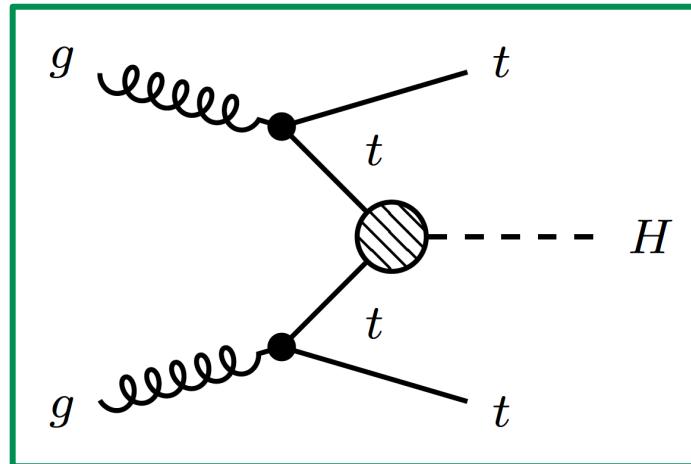
- **Higgs boson production modes**
 - Existing ATLAS analyses probe different production modes

HVV coupling in
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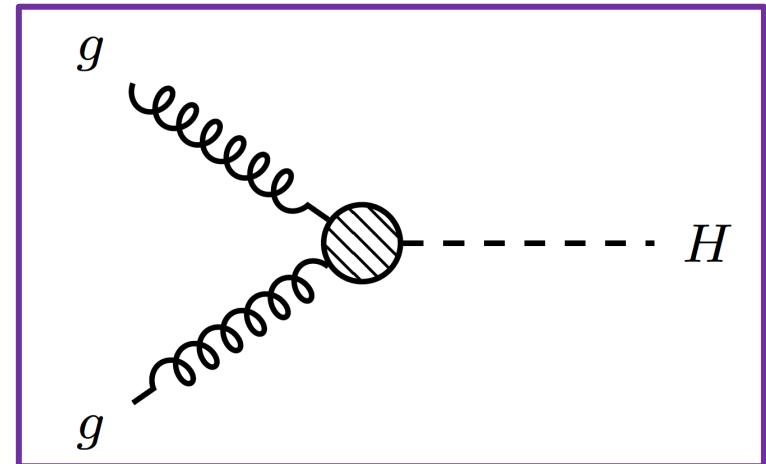
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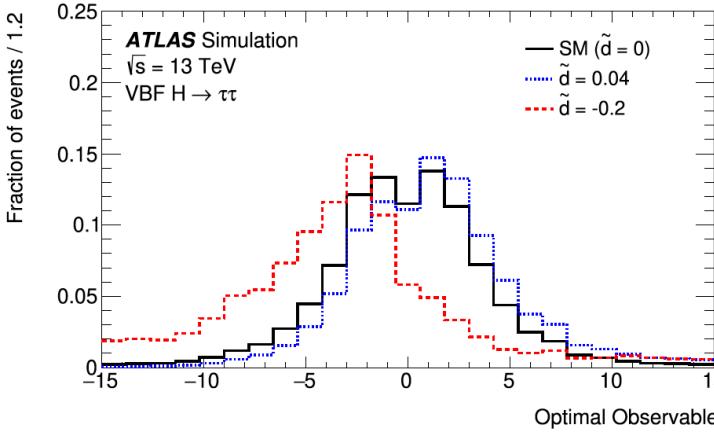


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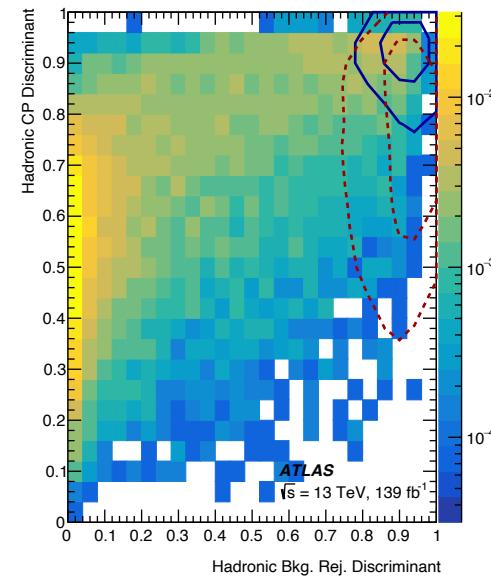
Searching for signs of CP-violation in the Higgs boson couplings with other SM particles

- **Higgs boson production modes**
 - Existing ATLAS analyses probe different production modes
- Theoretical Framework: **Effective Field Theory (EFT)** → constraint coupling or CP-mixing angle
- **Observables Sensitive to CP-odd effects**
 - Hawk basis: \tilde{d} parameter
 - Optimal Observable



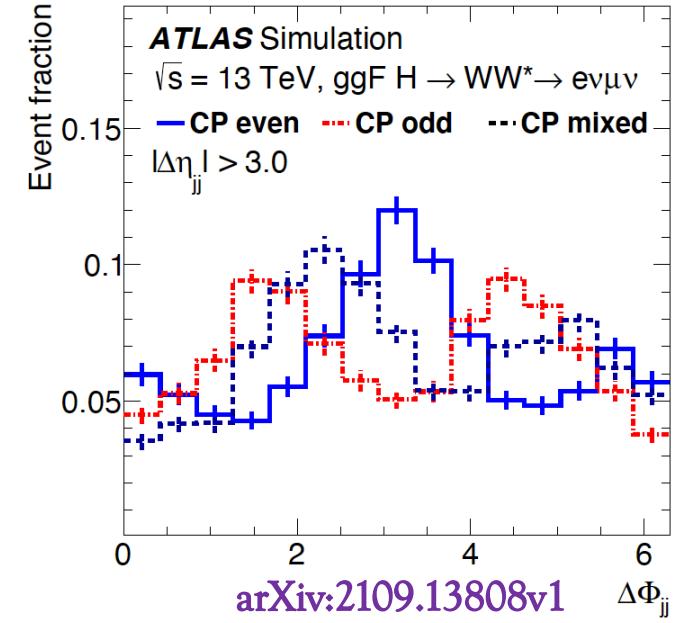
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- HC basis → angle κ_t and α
- BDT: CP-even vs. CP-odd



Phys. Rev. Lett. 125 (2020) 061802

- HC basis → angle κ_{gg} and α
- $\Delta\phi_{jj}$



arXiv:2109.13808v1

CP properties of the Higgs boson

Searching for signs of CP-violation in the Higgs boson couplings with other SM particles

- **Higgs boson production modes**
 - Existing ATLAS analyses probe different production modes
- **Results**

