Higgs Spin, Parity and CP at the LHC

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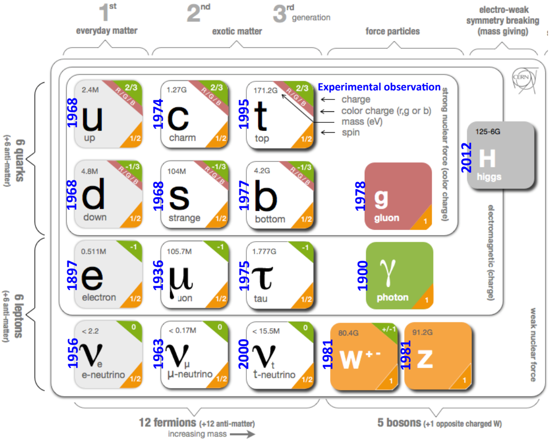
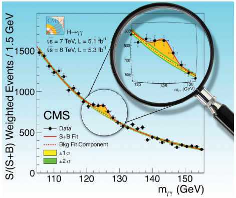
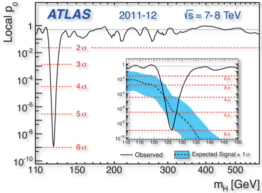
The 40th International Symposium on Physics in Collision
Aachen, September 15, 2021

The Higgs boson: est. 2012

- Discovery of the Higgs boson by the ATLAS and CMS collaborations announced at CERN in July 4th 2012

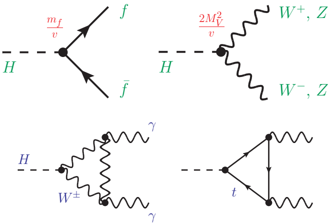


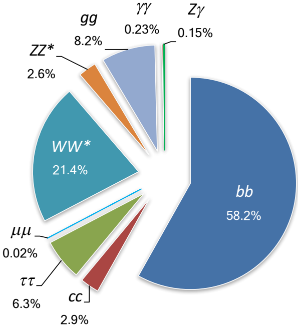




- With the Higgs boson discovery, all the particles in the Standard Model (SM) have been observed experimentally

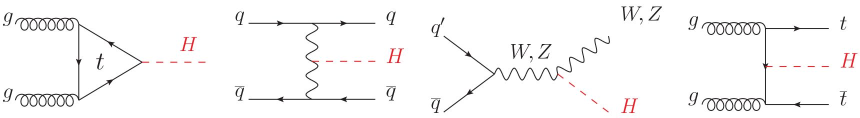
Higgs boson couplings and decays

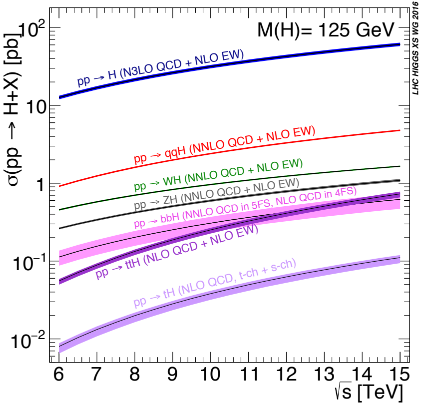




- Once the Higgs boson mass is measured, we have concrete predictions from the SM for:
  - Coupling strengths to vector bosons and fermions
  - Decays and production modes
- Not directly coupling to photons and gluons → Can decay via loops involving preferentially heavy particles (top, W bosons)
- Main decay channels:
  - High resolution channels: $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*(\rightarrow 4\ell)$
  - $H \rightarrow WW^*(\rightarrow \ell\nu\ell\nu)$, $H \rightarrow \tau\tau$: also observed in Run-1
  - $H \rightarrow b\bar{b}$: observation in Run-2

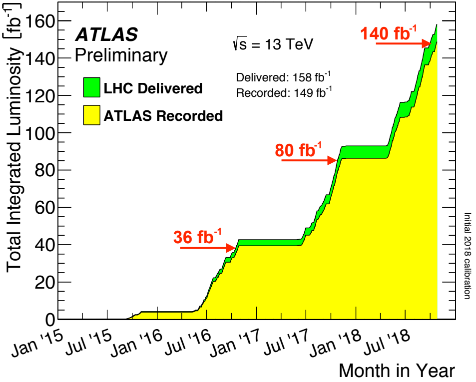
Production mechanisms

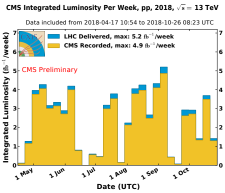


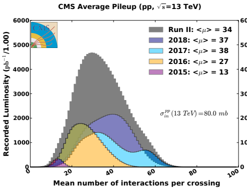


- Main production modes at the LHC:
  - Gluon fusion (ggF): dominant production mode
    $\sim 7\times10^6$ ggF events in Run-2
  - Vector boson fusion (VBF):
    $\sim$7% of the total cross-section
    $\sim 500\times10^3$ VBF events in Run-2
  - VH associated production: $\sim$4%
    $\sim 300\times10^3$ VH events in Run-2
  - $t\bar{t}H$ associated production: $\sim$1%
    $\sim 70\times10^3$ $t\bar{t}H$ events in Run-2
- Much rarer modes: $b\bar{b}H$, tHq

Run-2 in ATLAS and CMS

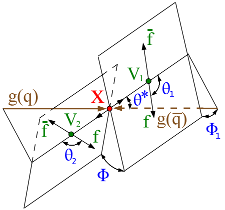






- This talk: overview of recent ATLAS and CMS results on Higgs boson *CP* properties, some of them using $\sim$140 fb^{-1} of data
- All results available at the ATLAS HiggsPublicResults and CMS PhysicsResultsHIG webpages

Exploring Higgs boson Spin and Parity



- Observables typically used to probe spin and parity:
  - Production angles (sensitive to spin, polarization)
  - Decay angles (sensitive to *CP* properties)
  - Invariant masses (mostly for background rejection)
- Exploit correlations between decay products and with other particles involved in Higgs boson production

- Commonly used as input to more complex methods (MVAs, etc)
- Many cases combining two different BDTs or discriminants, with one dedicated to background rejection
- Matrix Element Likelihood Approach (MELA) (PRD 94, 055023)

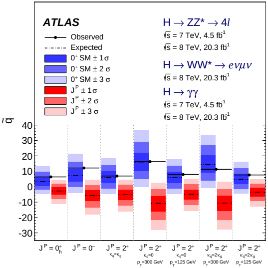
$$\mathcal{D}_{\rm alt} = \frac{\mathcal{P}_{\rm A}(\vec{\Omega})}{\mathcal{P}_{\rm A}(\vec{\Omega}) + \mathcal{P}_{B}(\vec{\Omega})}$$

$$\mathcal{D}_{\rm int} = \frac{\mathcal{P}_{\rm int}(\vec{\Omega})}{\mathcal{P}_{\rm A}(\vec{\Omega}) + \mathcal{P}_{\rm B}(\vec{\Omega})}$$

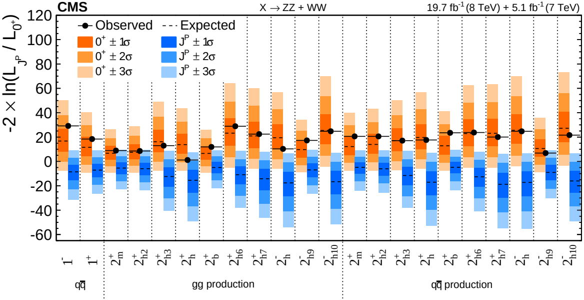
- Matrix Element Method (MEM): event by event discriminator built upon matrix elements → Probability that the event matches a given hypothesis
- Can build discriminants ($\mathcal{D}$) to disentangle two different hypothesis A and B or their interference
  - $\mathcal{P}_{\mathcal{A}/\mathcal{B}}$: probability of an event with 4-momenta $\overrightarrow{\Omega}$ under hypothesis *A* or *B*

Higgs boson spin/parity

EPJC75 (2015) 476



Phys. Rev. D 92 (2015) 012004



- Higgs boson spin and parity quantum numbers studied since Run 1
- Using angular distributions, invariant masses, etc, in $H \to ZZ^* \to 4\ell$, $H \to WW^* \to \ell\nu\ell\nu$, $H \to \gamma\gamma$ to test various J^P hypotheses against each other
- Strong preference in data for the SM $J^P = 0^+$ hypothesis
- All non-SM hypotheses excluded at >99% confidence level (CL)

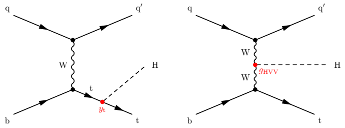
Higgs boson Charge Conjugation/Parity (CP)

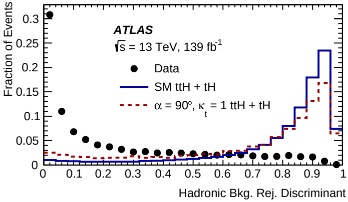
- SM prediction: CP-even ($J^{CP} = 0^{++}$, scalar)
- Signs of a CP-odd ($J^{CP} = 0^{+-}$, pseudoscalar) couplings to SM particles (or an CP-odd/even admixture) would be a indication of Beyond the SM (BSM) physics
- Motivation: New sources of CP violation needed to explain baryon asymmetry in the university (besides the CKM matrix)

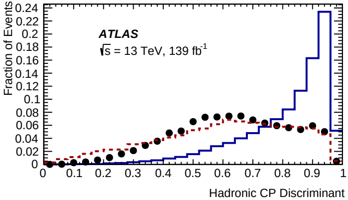
→ **Searches for CP-odd component in the Higgs boson interactions:**

  - Coupling to bosons: HVV and Hgg effective vertex
  - Yukawa coupling to fermions: Hff
  - Tested both in Higgs boson production and decay

- Final states:
  - $H \to ZZ^* \to 4\ell$: clean channel, full reconstruction of the system
  - $H \to WW^* \to e\nu\mu\nu$: clean channel but $E_{\mathrm{T}}^{\mathrm{miss}}$ from the neutrinos
  - $H \to \tau\tau$: large branching fraction, also with neutrino from τ decays
  - $t\bar{t}H$ production with $H \to \gamma\gamma$







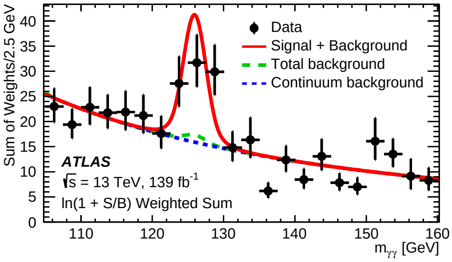
- Target signal: $t\bar{t}H + tH$
  - tH: lower cross-section than $t\bar{t}H$ but potentially sensitive to BSM effects
- Top quark Yukawa coupling parametrized as:

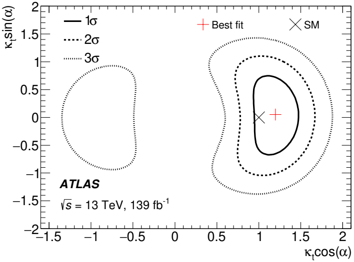
$$\mathcal{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t \kappa_t \left[\cos(\alpha) + i\sin(\alpha)\gamma_5\right]\psi_t\right\} H$$

  - κ_t: coupling parameter (SM: $\kappa_t = 1$)
  - α: *CP* mixing angle (SM: $\alpha = 0$; *CP*-odd: $\alpha = 90^o$)
- Two separate channels ($0/\geq 1$ leptons)
- Categories defined using two BDTs:
  - Background rejection: $t\bar{t}H$ vs. main backgrounds ($\gamma\gamma$+jets, $t\bar{t}\gamma\gamma$)
  - *CP* BDT: separate *CP*-odd and *CP*-even couplings in the signal

Hff: $t\bar{t}H/tH$ production, $H \to \gamma\gamma$

PRL 125 (2020) 061802





- Simultaneous fit to $m_{\gamma\gamma}$ in all categories
  - Free floating background model and normalization parameters
  - Higgs couplings to photons and gluons constrained by the Run 2 combination results in PRD 101 (2020) 012002 (up to 80 fb^{-1})
  - Dominated by statistical uncertainties
- Results:
  - Excluding $|\alpha| > 43^o$ at 95% CL
  - Pure CP-odd coupling excluded at 3.9σ

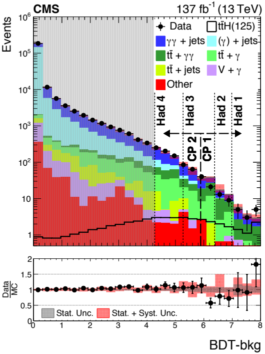
Hff: $t\bar{t}H$ production, $H \to \gamma\gamma$

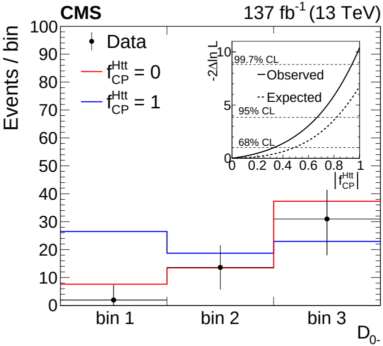
PRL 125 (2020) 061801

- Htt CP structure parametrized as:

$$\mathcal{A}(\mathrm{Htt}) = -\frac{m_\mathrm{t}}{v}\bar{\psi}_\mathrm{t}\left(\kappa_\mathrm{t} + \mathrm{i}\tilde{\kappa}_\mathrm{t}\gamma_5\right)\psi_\mathrm{t} \qquad f_{\mathrm{CP}}^{\mathrm{Htt}} = \frac{|\tilde{\kappa}_\mathrm{t}|^2}{|\kappa_\mathrm{t}|^2 + |\tilde{\kappa}_\mathrm{t}|^2}\,\mathrm{sign}(\tilde{\kappa}_\mathrm{t}/\kappa_\mathrm{t})$$

  - $\kappa_t/\tilde{\kappa}_t$: CP-even/odd Yukawa coupling $\longrightarrow$ Combined as f_{CP}^{Htt}
- Using MELA techniques, building categories with a BDT to separate CP-odd/even contributions ($\mathcal{D}_{0-}$) plus another BDT for background rejection
- Excluding $|f_{CP}^{\mathrm{Htt}}| > 0.67$ at 95% CL and pure CP-odd interactions by 3.2σ





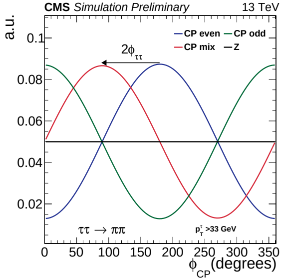
Hff: $H \to \tau\tau$

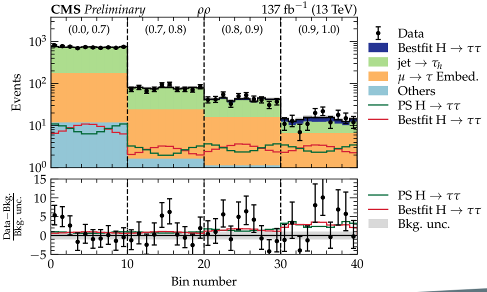
CMS-PAS-HIG-20-006

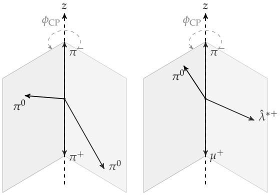
- $H\tau\tau$ coupling split into *CP*-odd/even components:

$$\mathcal{L}_Y = -\frac{m_\tau H}{v}(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau) \qquad \tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

  - SM: $\phi_{\tau\tau}=0$; *CP*-odd: $\phi_{\tau\tau}=90^o$
- Discriminant: angle between the τ decay planes (ϕ_{CP})
  - Approximations based on impact parameter or π^0 methods due to the neutrinos in the τ decays
- MVAs to separate the signal from background events and distinguish between the hadronic τ decay modes

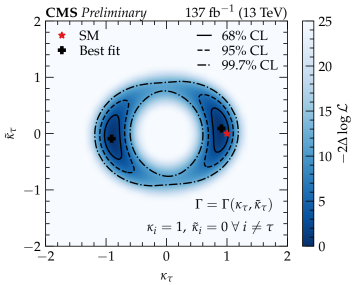


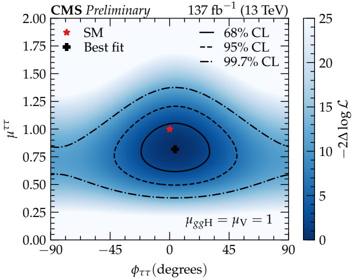


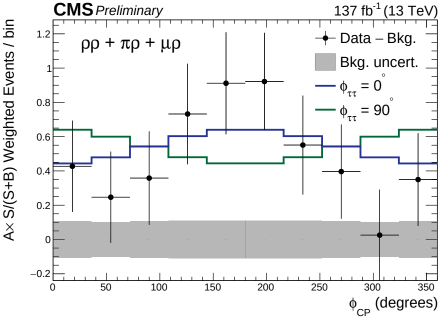


Hff: $H \to \tau\tau$

CMS-PAS-HIG-20-006







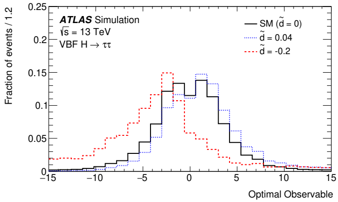
- Observed result: $\phi_{\tau\tau} = 4 \pm 17^o$ (dominated by statistical uncertainties)
- Excluding $\phi_{\tau\tau} \notin [-32^o, 40^o]$ at 95% CL
- Pure *CP*-odd excluded at 3.2σ
- Cross-check also floating the signal strength $\mu_{\tau\tau}$

HVV: VBF production, $H \to \tau\tau$ PLB 805 (2020) 135426 (36 fb^{-1})

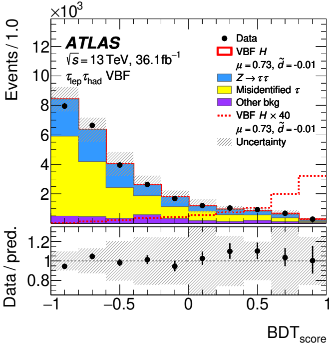
- Strength of CP violation described with a single $\tilde{d}$ parameter:

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

- Using the Optimal Observable (PLB 306 (1993) 411) as discriminant
- Experimentally built with 4-momenta of the Higgs boson and the two VBF tagging jets

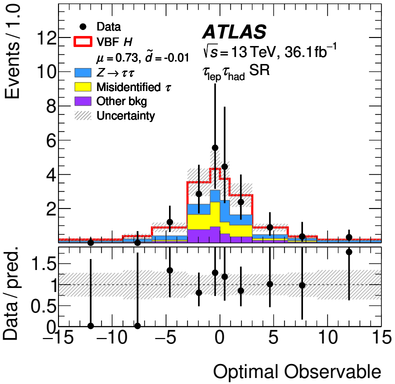


$$O_{\mathrm{opt}} = \frac{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}$$



- Considering leptonic and hadronic tau decays $\to$ 4 channels
- VBF topology selection plus extra $E_{\mathrm{T}}^{\mathrm{miss}}$ and b-veto requirements to reduce backgrounds
- BDT to further enhance VBF signal over Z and misidentified τ backgrounds

HVV: VBF production, $H \rightarrow \tau\tau$ PLB 805 (2020) 135426 (36 fb^{-1})



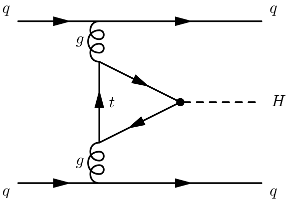
- Fit $\mathcal{O}_{\text{opt}}$ distributions in 4 high BDT categories. Not relying on signal rates, only shape information
- Low BDT categories plus dedicated control regions used to estimate the $Z(\tau\tau)$, top and misidentified τ backgrounds
- Distributions compatible with the SM

- $\tilde{d}$ constrained at 68% confidence level (CL) to $[-0.090, 0.035]$ (exp: $[-0.035, 0.033]$)
- Mostly limited by systematics, such as jet reconstruction uncertainties
- Earlier results by CMS in PRD 100 (2019) 112002

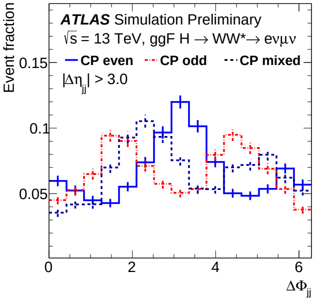
Hgg: ggF+2-jet, $H \to WW^*$

ATLAS-CONF-2020-055 (36 fb^{-1})

- Higgs boson production in association with two jets via the fusion of two gluons, with $H \to WW^* \to e\nu\mu\nu \Rightarrow$ Constrain the *CP* properties of the effective Hgg vertex
- Effective lagrangian of the Higgs-gluon interaction:



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

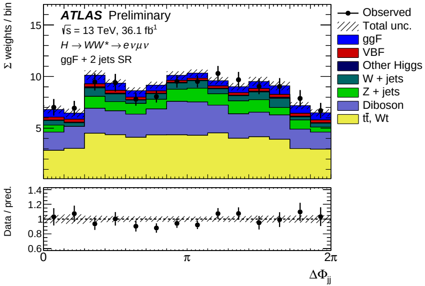


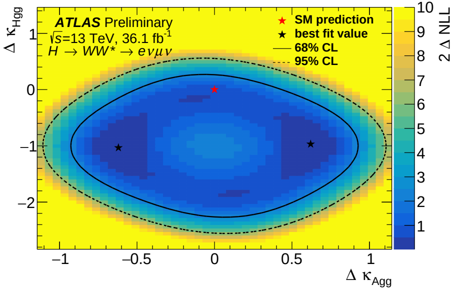
Scenario	Parameters
CP-even (SM)	$\kappa_{Hgg} = 1, \kappa_{Agg} = 0$
CP-odd	$\kappa_{Hgg} = 0, \kappa_{Agg} = 1$
CP-mixed	$\kappa_{Hgg} = \frac{1}{\sqrt{2}}, \kappa_{Agg} = \frac{1}{\sqrt{2}}$

- Using azimuthal separation between the two jets as discriminant

Hgg: ggF+2-jet, $H \to WW^*$

ATLAS-CONF-2020-055 (36 fb^{-1})



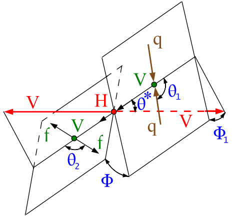


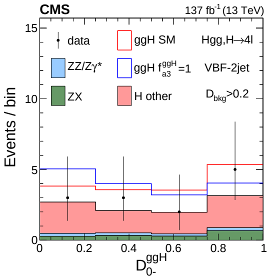
- BDT used to reduce background contributions
- 12 categories defined in BDT score (increasing signal purity) and $|\Delta\eta_{jj}|$ (to enhance sensitivity to *CP* effects)
  - Low BDT categories plus dedicated control regions to normalize the top, *WW* and $Z(\tau\tau)$ backgrounds
- Using both shape and rate information in a maximum likelihood fit to the $\Delta\Phi_{jj}$ distributions in each category
- Ratio of the *CP*-odd to *CP*-even coupling strength scale factors of the effective Higgs-gluon vertex: $\kappa_{Agg}/\kappa_{Hgg}$=0.0±0.4(stat.)±0.3(syst.)

Exploring CP in $H \to ZZ^* \to 4\ell$ decay

arXiv:2104.12152

- Using production in association with 2 jets, W/Z boson or top quark to explore CP properties of HVV, Hgg and Htt vertices





- HVV coupling parametrization:

$$A(\mathrm{HV_1V_2}) = \frac{1}{v}\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}}(q_{\mathrm{V1}}+q_{\mathrm{V2}})^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

  - a_1: SM; a_2: CP-even anomalous coupling; a_3: CP-odd anomalous coupling;

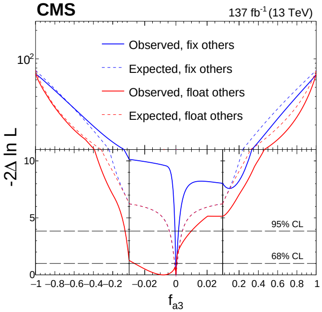
- Effective fractional cross-section:

$$f_{ai}^{\mathrm{VV}} = \frac{|a_i^{\mathrm{VV}}|^2 \alpha_{ii}^{(2e2\mu)}}{\sum_j |a_j^{\mathrm{VV}}|^2 \alpha_{jj}^{(2e2\mu)}} \ \mathrm{sign}\left(\frac{a_i^{\mathrm{VV}}}{a_1}\right)$$

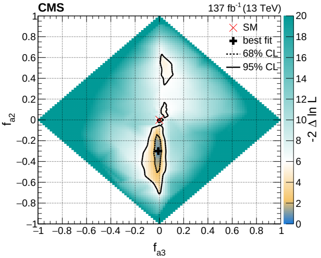
- Use BDTs and MELA observables to create categories rich in VBF / VH / $t\bar{t}H$ events and increase sensitivity to CP effects
  - Combining different MELA discriminants for background and different signal hypotheses

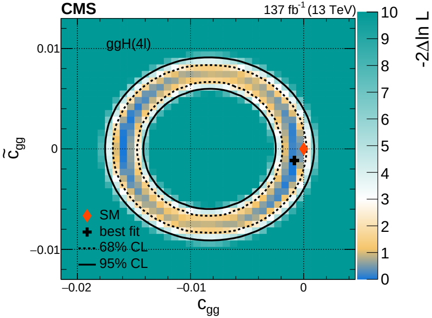
Exploring CP in $H \to ZZ^* \to 4\ell$ decay

arXiv:2104.12152



- Strategy: Scan over single or multiple parameters (floating or fixing the rest)
- HVV coupling probed with VBF and VH production
- Using ggF production to also probe Hgg coupling:

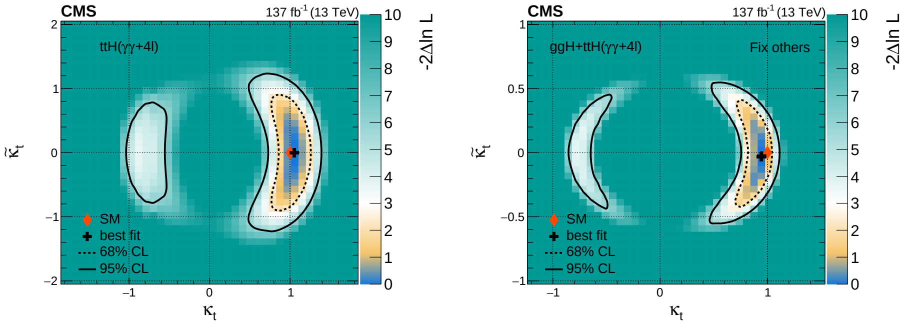




Exploring CP in $H \to ZZ^* \to 4\ell$ decay

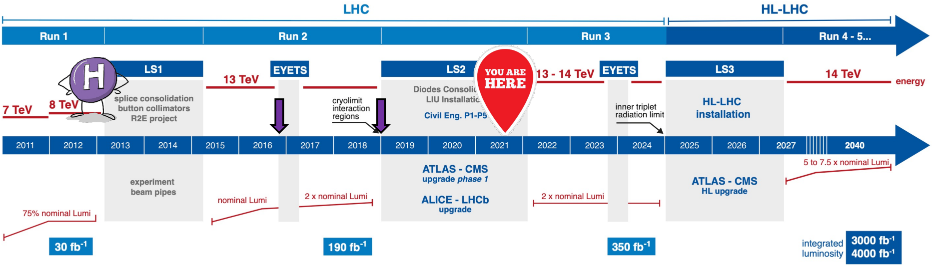
arXiv:2104.12152

- Results combined with $t\bar{t}H(\gamma\gamma)$ to constraint Htt CP structure $\to$ $f_{CP}^{\text{Htt}} = 0.00 \pm 0.33$
- Incorporating also information from ggF production (top contribution to quantum loop): $f_{CP}^{\text{Htt}} = -0.04 \pm 0.38$
- All results consistent with SM predictions



Summary

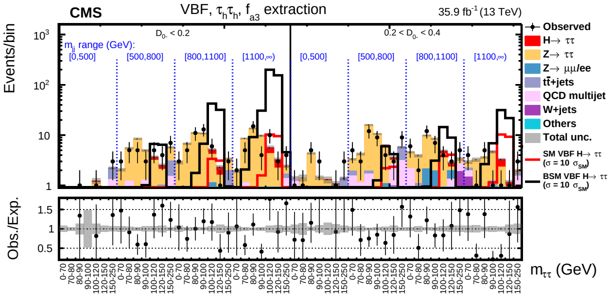
- More than 9 years after the discovery of the Higgs boson
- No hint for BSM effects in the Higgs sector... *yet*
- Rich program of analyses targeting the exploration of *CP* violation in Higgs interactions
- Different parametrizations used for the results → Would benefit from common framework for interpretations (à la STXS)
- Many of these measurements using a fraction of Run 2 data and limited by statistics → Stay tuned
- Still a factor 20 more data to be acquired at the LHC!

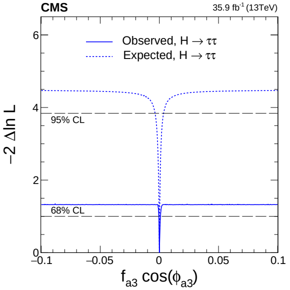


Backup Slides

HVV: $H \to \tau\tau$

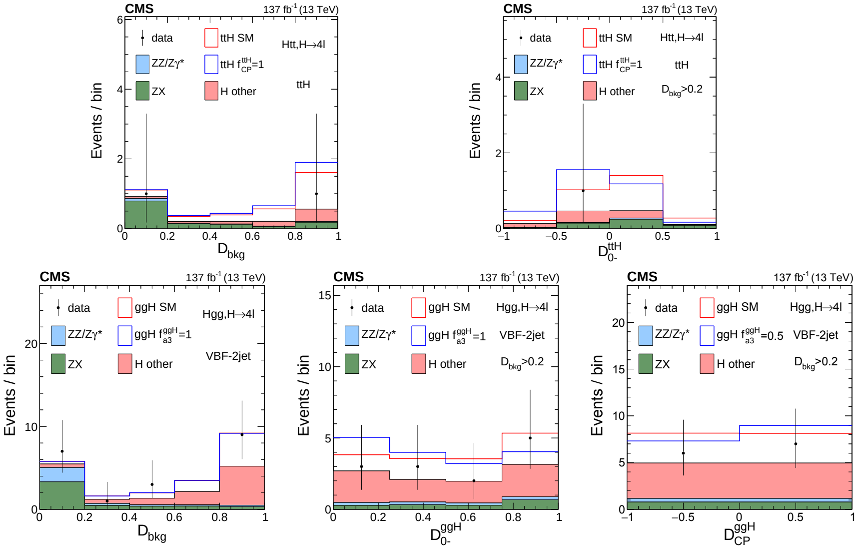
PRD 100 (2019) 112002





Exploring CP in $H \to ZZ^* \to 4\ell$ decay

arXiv:2104.12152



Exploring CP in $H \to ZZ^* \to 4\ell$ decay

arXiv:2104.12152

Category	Selection	Observables $\vec{x}$ for fitting
Scheme 1		
VBF-1jet	$\mathcal{D}^{\mathrm{VBF}}_{\mathrm{1jet}} > 0.7$	$\mathcal{D}_{\mathrm{bkg}}$
VBF-2jet	$\mathcal{D}^{\mathrm{VBF}}_{\mathrm{2jet}} > 0.5$	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}^{\mathrm{VBF}}_{\mathrm{2jet}}, \mathcal{D}^{\mathrm{ggH}}_{0-}, \mathcal{D}^{\mathrm{ggH}}_{\mathrm{CP}}$
VH-hadronic	$\mathcal{D}^{\mathrm{VH}}_{\mathrm{2jet}} > 0.5$	$\mathcal{D}_{\mathrm{bkg}}$
VH-leptonic	see Section 3	$\mathcal{D}_{\mathrm{bkg}}$
$\mathrm{t\bar{t}H}$-hadronic	see Section 3	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}^{\mathrm{t\bar{t}H}}_{0-}$
$\mathrm{t\bar{t}H}$-leptonic	see Section 3	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}^{\mathrm{t\bar{t}H}}_{0-}$
Untagged	none of the above	$\mathcal{D}_{\mathrm{bkg}}$
Scheme 2		
Boosted	$p_{\mathrm{T}}^{4\ell} > 120\,\mathrm{GeV}$	$\mathcal{D}_{\mathrm{bkg}}, p_{\mathrm{T}}^{4\ell}$
VBF-1jet	$\mathcal{D}^{\mathrm{VBF}}_{\mathrm{1jet}} > 0.7$	$\mathcal{D}_{\mathrm{bkg}}, p_{\mathrm{T}}^{4\ell}$
VBF-2jet	$\mathcal{D}^{\mathrm{VBF}}_{\mathrm{2jet}} > 0.5$	$\mathcal{D}^{\mathrm{EW}}_{\mathrm{bkg}}, \mathcal{D}^{\mathrm{VBF+dec}}_{\mathrm{0h+}}, \mathcal{D}^{\mathrm{VBF+dec}}_{0-}, \mathcal{D}^{\mathrm{VBF+dec}}_{\Lambda 1}, \mathcal{D}^{\mathrm{Z}\gamma,\mathrm{VBF+dec}}_{\Lambda 1}, \mathcal{D}^{\mathrm{VBF}}_{\mathrm{int}}, \mathcal{D}^{\mathrm{VBF}}_{\mathrm{CP}}$
VH-hadronic	$\mathcal{D}^{\mathrm{VH}}_{\mathrm{2jet}} > 0.5$	$\mathcal{D}^{\mathrm{EW}}_{\mathrm{bkg}}, \mathcal{D}^{\mathrm{VH+dec}}_{\mathrm{0h+}}, \mathcal{D}^{\mathrm{VH+dec}}_{0-}, \mathcal{D}^{\mathrm{VH+dec}}_{\Lambda 1}, \mathcal{D}^{\mathrm{Z}\gamma,\mathrm{VH+dec}}_{\Lambda 1}, \mathcal{D}^{\mathrm{VH}}_{\mathrm{int}}, \mathcal{D}^{\mathrm{VH}}_{\mathrm{CP}}$
VH-leptonic	see Section 3	$\mathcal{D}_{\mathrm{bkg}}, p_{\mathrm{T}}^{4\ell}$
Untagged	none of the above	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}^{\mathrm{dec}}_{\mathrm{0h+}}, \mathcal{D}^{\mathrm{dec}}_{0-}, \mathcal{D}^{\mathrm{dec}}_{\Lambda 1}, \mathcal{D}^{\mathrm{Z}\gamma,\mathrm{dec}}_{\Lambda 1}, \mathcal{D}^{\mathrm{dec}}_{\mathrm{int}}, \mathcal{D}^{\mathrm{dec}}_{\mathrm{CP}}$