Study of the CP property of the Higgs boson to electroweak boson coupling in the VBF $H\rightarrow\gamma\gamma$ channel with the ATLAS detector

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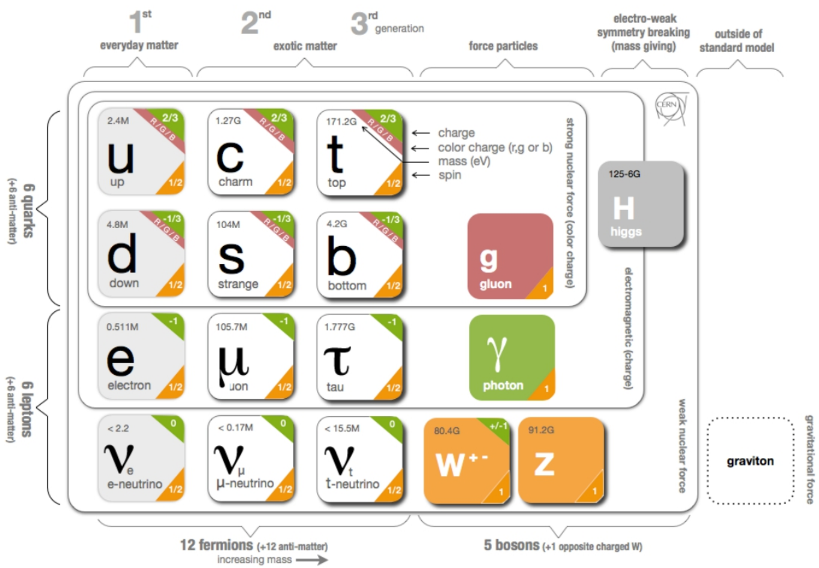
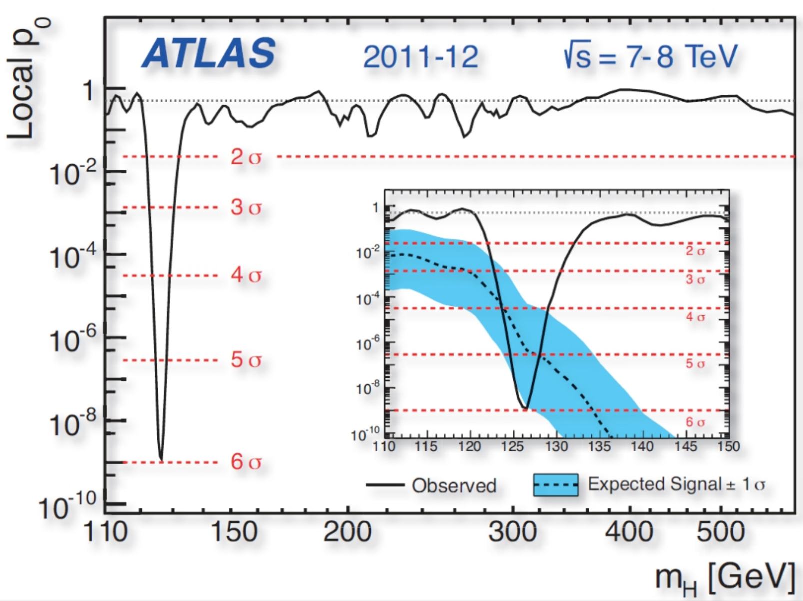
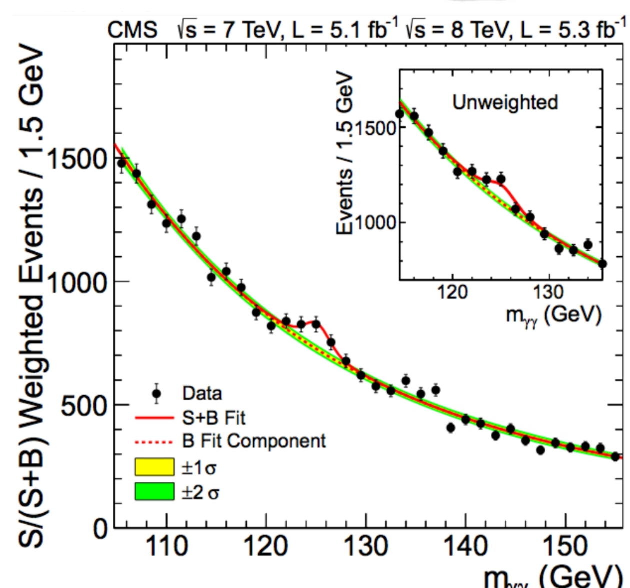
The Higgs boson



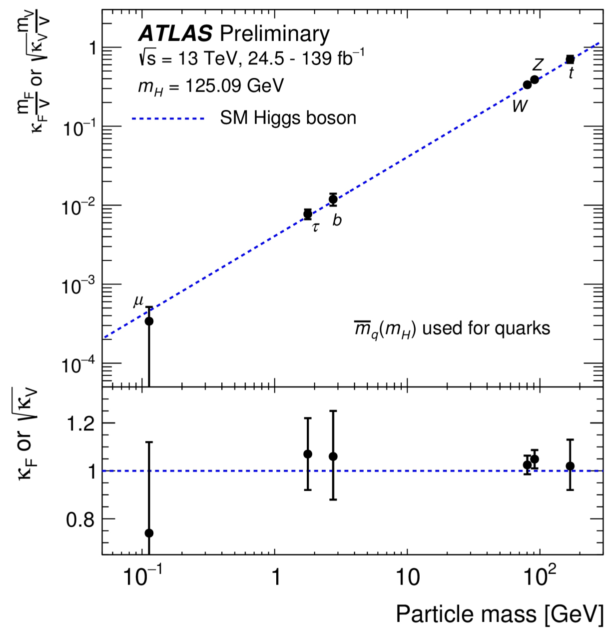
- The SM is a successful model of the particle physics
- The Higgs boson play the unique role in the SM of giving mass to other particles via EW SSB
- Was discoveried by ATLAS and CMS in 2012 within bosonic channel

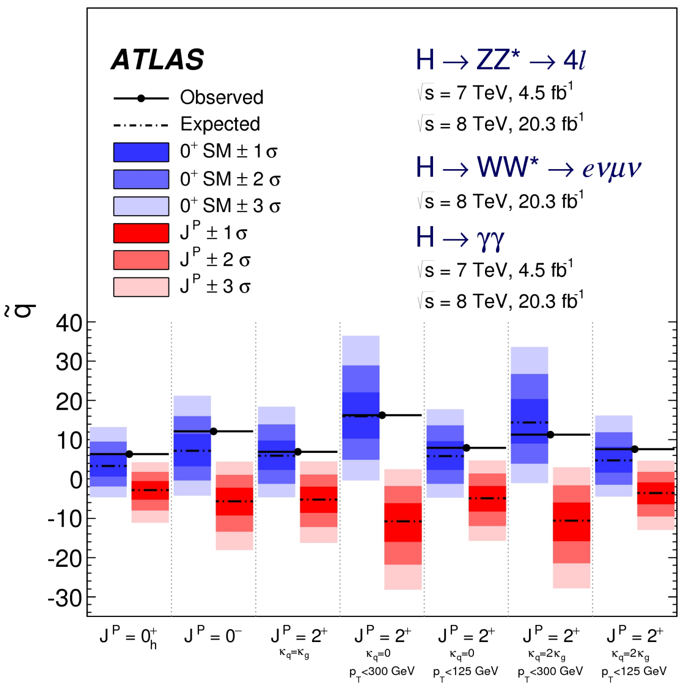


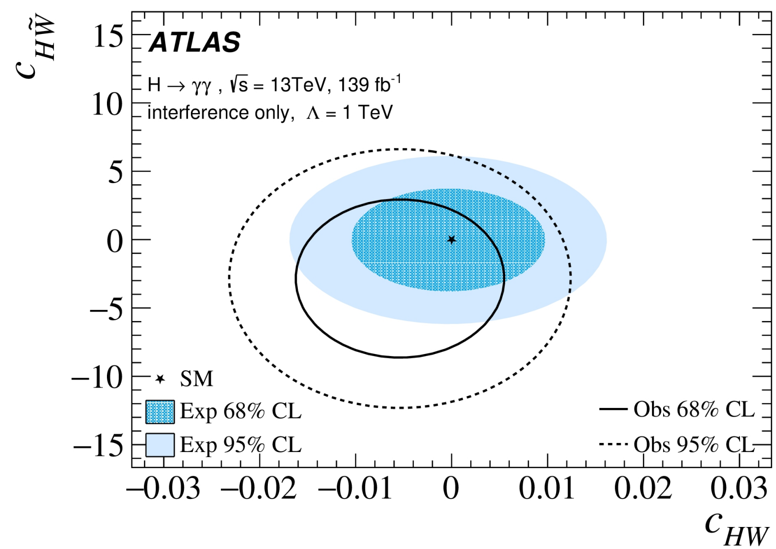


Higgs boson properties

- The properties of the Higgs boson has been precisely measured with LHC run-I/II data since the discovery 10yrs ago
- Great agreement between SM prediction with measurements
- Still room for new physics/new interactions
  - One of the potential is CP-odd components

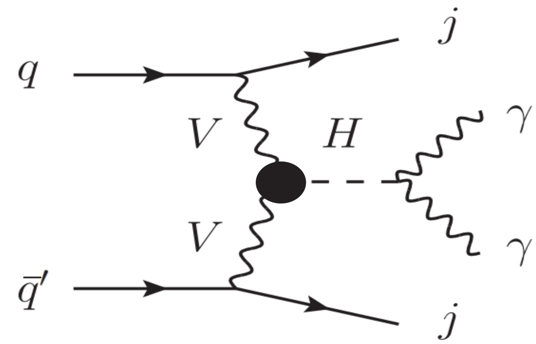






Motivation and theoretical framework

- **Motivation**
  - ✓ Study the CP structure of interactions between the Higgs boson and EWK gauge bosons



- **Explored two EFT bases**
  - ✓ HISZ basis
    - After EWSB, EFT Lagrangian can be written as

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

    - Dimensionless parameters introduced: d and $\tilde{d}$, with assumming $d = \tilde{d}$

$$\tilde{g}_{H\gamma\gamma} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d} \quad \text{and} \quad \tilde{g}_{H\gamma Z} = 0 . \qquad \mathcal{M} = \mathcal{M}_{SM} + \tilde{d} \cdot \mathcal{M}_{CP\text{-}odd}.$$

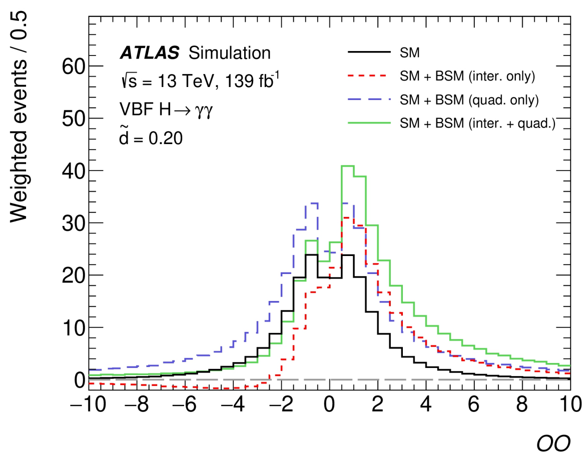
  - ✓ Warsaw basis

$$\mathcal{L}_{\text{SMEFT}}^{\text{CP-odd}} \supset \frac{c_{H\tilde{W}}}{\Lambda^2} H^\dagger H W^I_{\mu\nu} W^{\mu\nu I} + \frac{c_{H\tilde{B}}}{\Lambda^2} H^\dagger H B^A_{\mu\nu} B^{\mu\nu} + \frac{c_{H\tilde{W}B}}{\Lambda^2} H^\dagger \sigma^I H W^I_{\mu\nu} B^{\mu\nu}$$

    - VBF production is dominated by HWW vertex, analysis mainly explores $c_{H\widetilde{W}}$

- **CP sensitive variable**
  - ✓ Optimal Observable

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

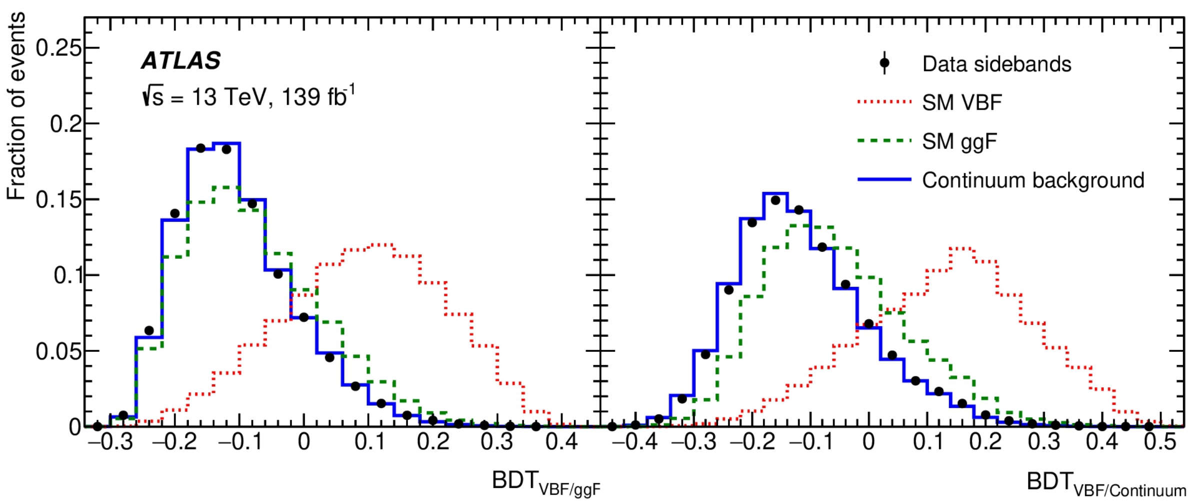


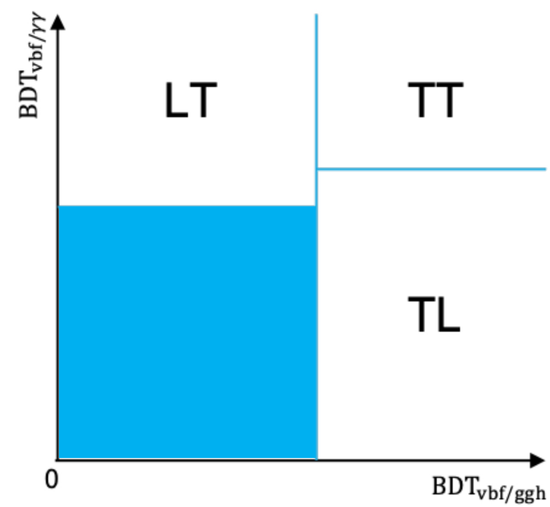
Analysis strategy

- Object definitions follow ATLAS $H\rightarrow\gamma\gamma$ recommendations
- Perform two independent BDT trainings:
  - *VBF/ggF*, *VBF/Continuum background* separation
  - Define *3 signal regions* based on BDT outputs
    - VBF purity increases by a factor of 10 with $\mathrm{BDT}_{\mathrm{vbf/ggh}}$ cut

Training variables

$$m_{\gamma\gamma},\ \Delta\eta_{jj},\ p_{\mathrm{Tt}}^{\gamma\gamma},\ p_{\mathrm{T}}^{Hjj},\ \Delta\phi(\gamma\gamma, jj),\ \Delta R_{\gamma j}^{\mathrm{min}},\ \eta^{Zepp}$$

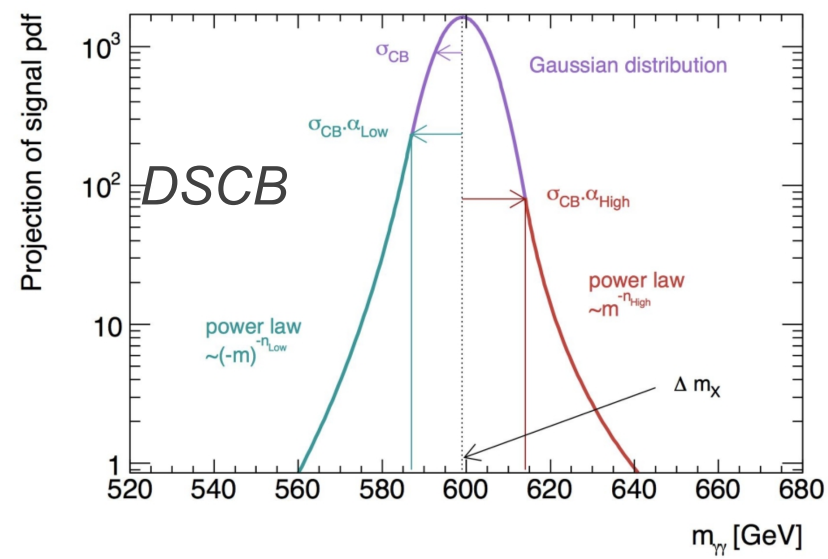




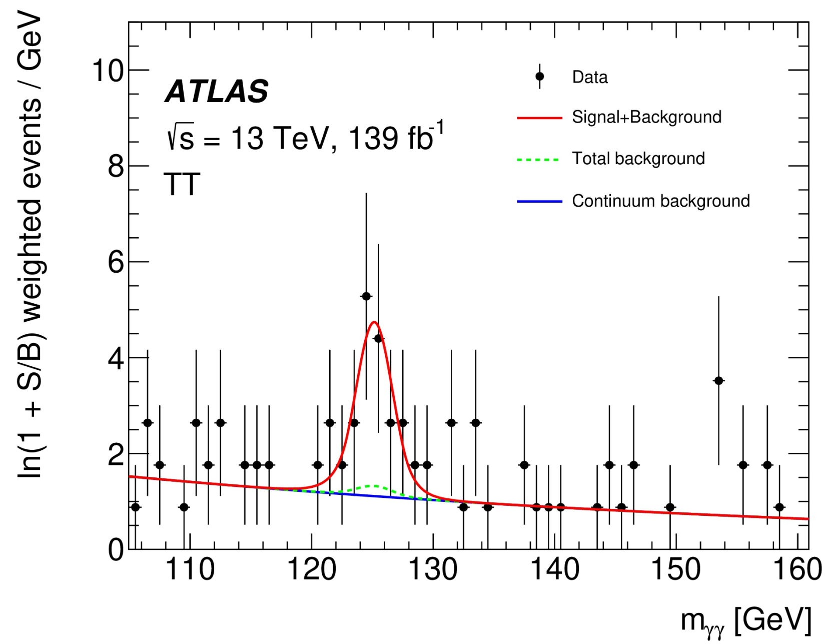
Signal and Background Modeling

- Both *signal* and *background* are modeled with analytic functions
- Signal is modeled with double-sided Crystal Ball function (DSCB)

$$
N\cdot\begin{cases}
e^{-t^2/2} & \text{if } -\alpha_{Low} \geq t \geq \alpha_{High} \\
\dfrac{e^{-0.5\alpha_{Low}^2}}{\left[\frac{\alpha_{Low}}{n_{Low}}\left(\frac{n_{Low}}{\alpha_{Low}}-\alpha_{Low}-t\right)\right]^{n_{Low}}} & \text{if } t < \text{-}t = \Delta m_X/\sigma_{CB},\ \Delta m_X = m_X - \mu_{CB} \\
\dfrac{e^{-0.5\alpha_{High}^2}}{\left[\frac{\alpha_{High}}{n_{High}}\left(\frac{n_{High}}{\alpha_{High}}-\alpha_{High}+t\right)\right]^{n_{High}}} & \text{if } t > \alpha_{High},
\end{cases}
$$

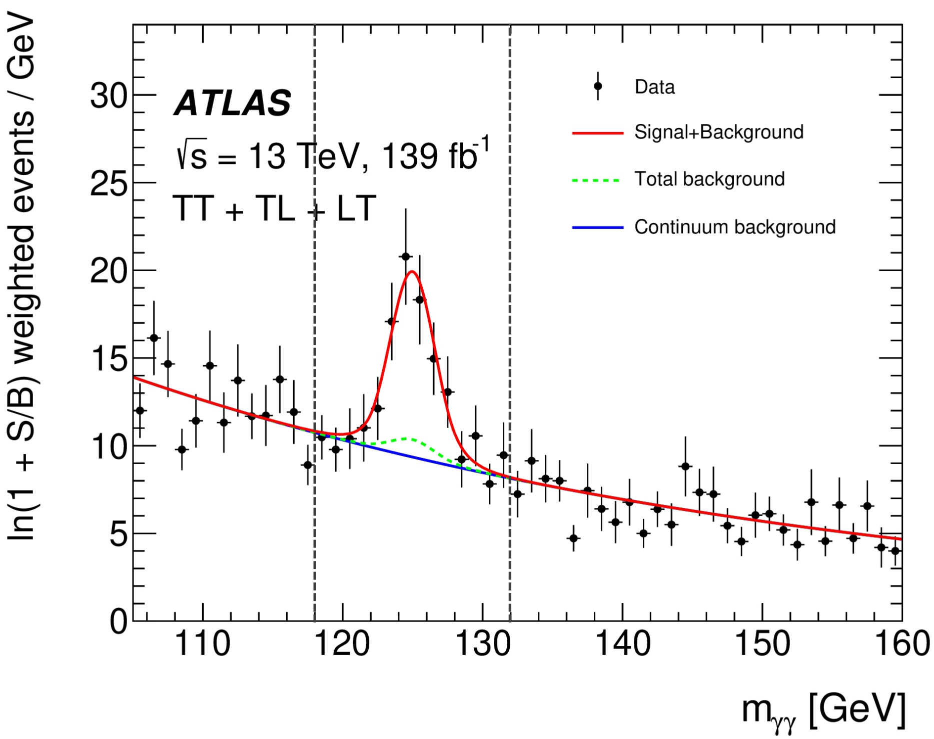


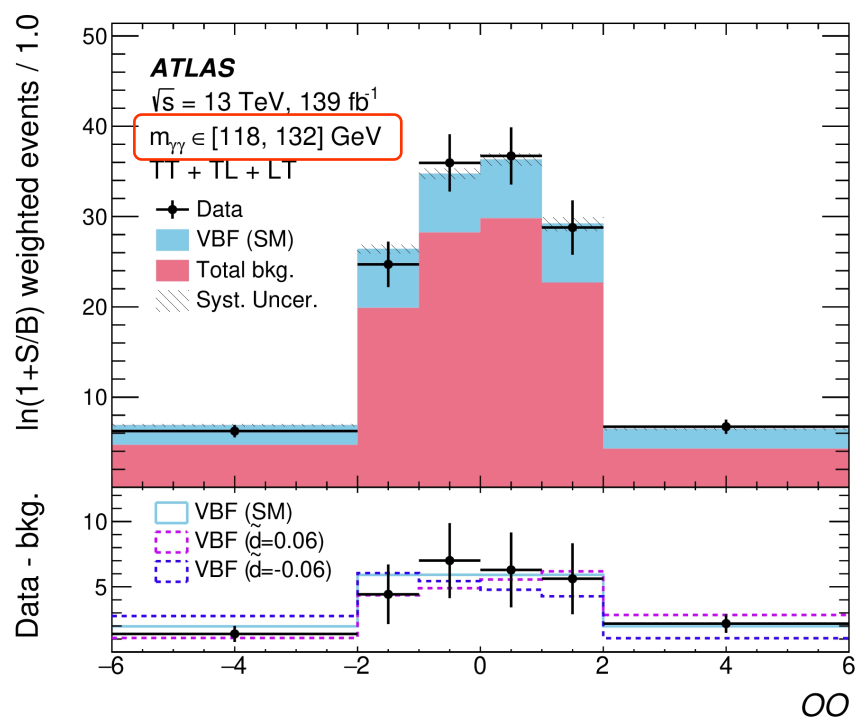
- The background is modeled with analytic function chosen from *power-law*/*Bernstein polynomial*/*ExpPoly* functions based on spurious signal test results
  - Spurious signal test is done with background-only distributions based on MC templates from γγ, γ+j, jj components
    - ✓ Templates are build with Gaussian process regression with the Gibbs kernel to reduce statistical uncertianties.



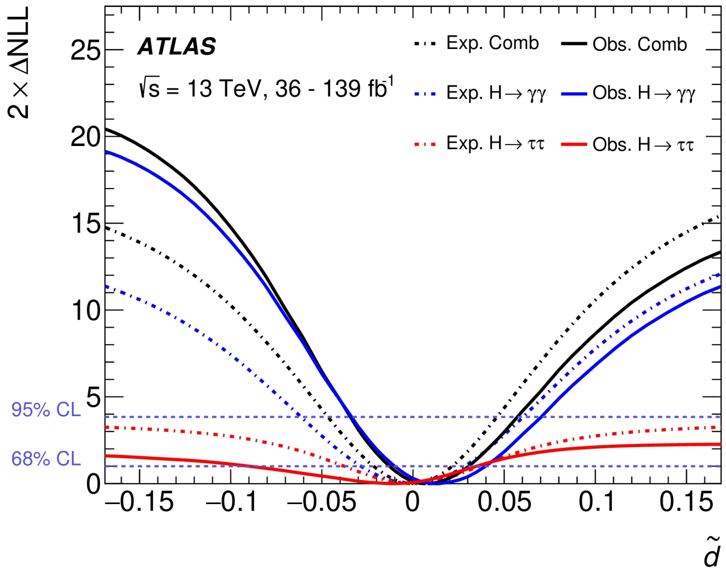
Statistical analysis

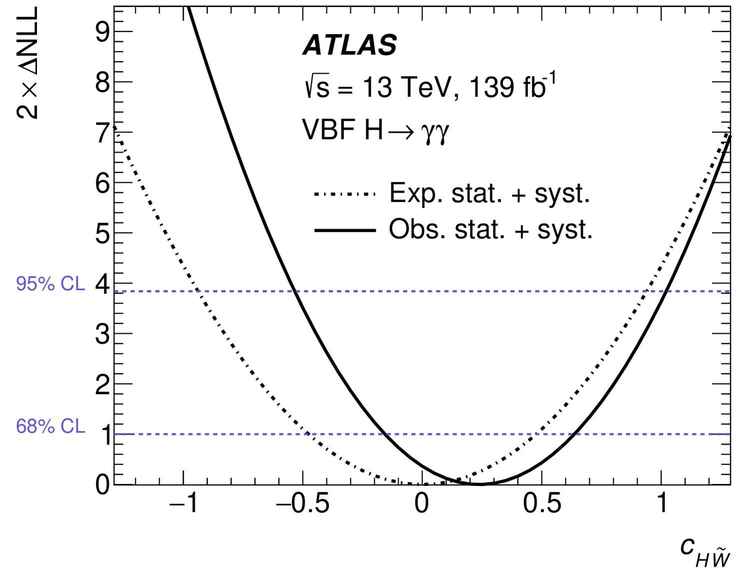
- Perform *signal*+*background* fit on $m_{\gamma\gamma}$ distributions in 6 *OO* bins in all 3 categories to extract VBF signal
  - *OO* bins are defined as [-∞, -2, -1, 0, 1, 2, ∞]
  - Test different $\tilde{d}$ or $c_{H\tilde{W}}$ values
  - Majority of sensitivity from high OO bins





Results

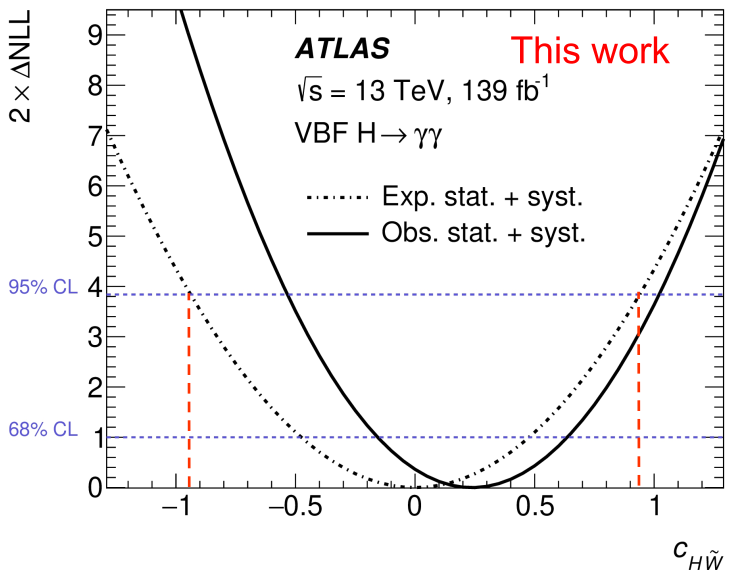


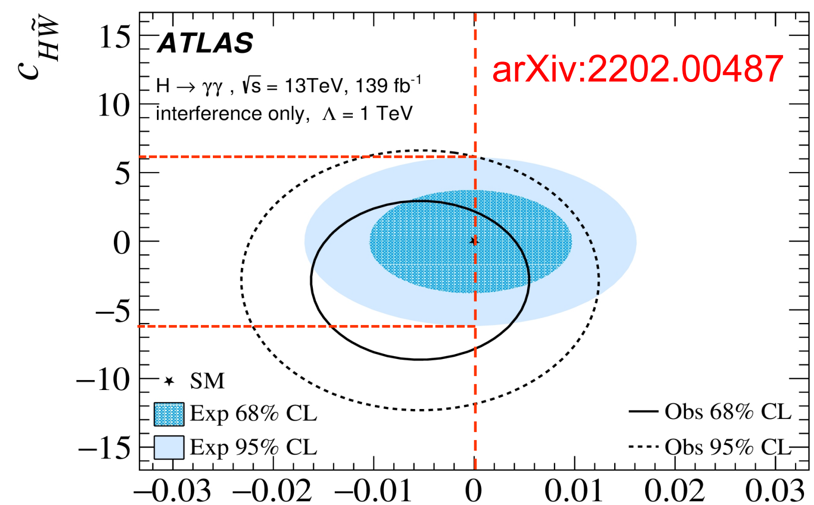


	68% (exp.)	95% (exp.)	68% (obs.)	95% (obs.)
$\tilde{d}$ (inter. only)	[−0.027, 0.027]	[−0.055, 0.055]	[−0.011, 0.036]	[−0.032, 0.059]
$\tilde{d}$ (inter.+quad.)	[−0.028, 0.028]	[−0.061, 0.060]	[−0.010, 0.040]	[−0.034, 0.071]
$\tilde{d}$ from $H\rightarrow\tau\tau$	[−0.038, 0.036]	–	[−0.090, 0.035]	-
Combined $\tilde{d}$	[−0.022, 0.021]	[−0.046, 0.045]	[−0.012, 0.030]	[−0.034, 0.057]
$c_{H\tilde{W}}$ (inter. only)	[−0.48, 0.48]	[−0.94, 0.94]	[−0.16, 0.64]	[−0.53, 1.02]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.48, 0.48]	[−0.95, 0.95]	[−0.15, 0.67]	[−0.55, 1.07]

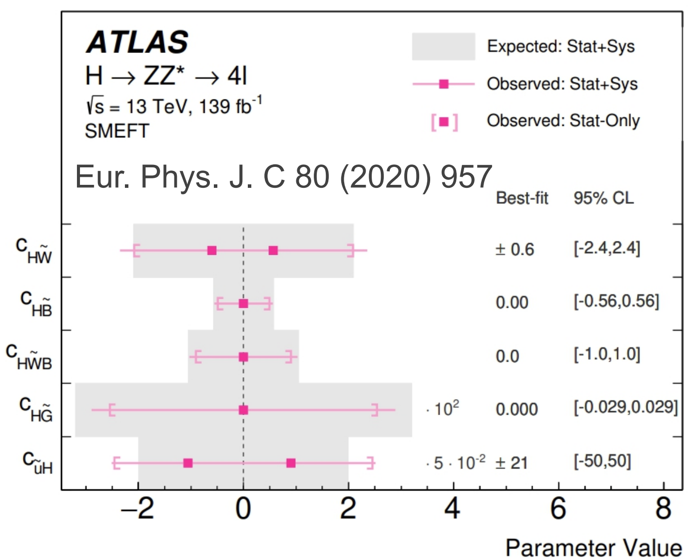
- No sign of CP violation is observed.
- Current most stringent constraints on CP-violation effect in HVV coupling
- Result for $\tilde{d}$ is further combined with $H\rightarrow\tau\tau$ analysis.

Compared to other channels





Roughly ~5 better constraint



Channels	Coupling	Observed	Expected
Phys. Rev. D 104, 052004 (2021) CMS VBF & VH & $H \to 4\ell$	$c_{H\Box}$	$0.04^{+0.43}_{-0.45}$	$0.00^{+0.75}_{-0.93}$
	c_{HD}	$-0.73^{+0.97}_{-4.21}$	$0.00^{+1.06}_{-4.60}$
	c_{HW}	$0.01^{+0.18}_{-0.17}$	$0.00^{+0.39}_{-0.28}$
	c_{HWB}	$0.01^{+0.20}_{-0.18}$	$0.00^{+0.42}_{-0.31}$
	c_{HB}	$0.00^{+0.05}_{-0.05}$	$0.00^{+0.03}_{-0.08}$
68% constraints	$c_{H\tilde{W}}$	$-0.23^{+0.51}_{-0.52}$	$0.00^{+1.11}_{-1.11}$
	$c_{H\tilde{W}B}$	$-0.25^{+0.56}_{-0.57}$	$0.00^{+1.21}_{-1.21}$
	$c_{H\tilde{B}}$	$-0.06^{+0.15}_{-0.16}$	$0.00^{+0.33}_{-0.33}$

Roughly ~2 better constraint

Summary

- The discovery of the Higgs boson in LHC open the new era of particle physics
- Precision measurement show good agreement with the SM predictions
- Study of CP properties would be the key ingradient for new physics searches
- Search for CP-odd component in VBF $H \rightarrow \gamma\gamma$ does not show significant excess with ATLAS run-II data
  - Only 5% data collected, more results in coming years

Keep looking like a child.
Be curious about the unknown.

Backup

Optimal observable

The effective $U(1)_Y$ and $SU(2)_{I_W,L}$ invariant Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_{\tilde{B}B}}{\Lambda^2}O_{\tilde{B}B} + \frac{c_{\tilde{W}W}}{\Lambda^2}O_{\tilde{W}W} + \frac{c_{\tilde{B}}}{\Lambda^2}O_{\tilde{B}}$$

three dimension-6 operators

$$O_{\tilde{B}B} = \Phi^+\hat{\tilde{B}}_{\mu\nu}\hat{B}^{\mu\nu}\Phi, \quad O_{\tilde{W}W} = \Phi^+\hat{\tilde{W}}_{\mu\nu}\hat{W}^{\mu\nu}\Phi, \quad O_{\tilde{B}} = (D_\mu\Phi)^+\hat{\tilde{B}}_{\mu\nu}D_\nu\Phi,$$

$$D_\mu = \partial_\mu + \tfrac{i}{2}g'B_\mu + ig\tfrac{\sigma_a}{2}W_\mu^a\sigma_a$$

After **SSB**, unitary gauge effective lagrangian can be written as **mass basis**

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

written into two dimensionless couplings $\tilde{d}$ and $\tilde{d}_B$

$$\tilde{g}_{H\gamma\gamma} = \frac{g}{2m_W}(\tilde{d}\sin^2\theta_W + \tilde{d}_B\cos^2\theta_W), \quad \tilde{g}_{H\gamma Z} = \frac{g}{2m_W}\sin 2\theta_W(\tilde{d} - \tilde{d}_B)$$

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

$$\tilde{d} = -\frac{m_W^2}{\Lambda^2}c_{\tilde{W}W}, \qquad \tilde{d}_B = -\frac{m_W^2}{\Lambda^2}tan^2\theta_W c_{\tilde{B}B}.$$

Optimal observable

an arbitrary choice $\tilde{d} = \tilde{d}_B$ is adopted

$$\tilde{g}_{H\gamma\gamma} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d} \quad \text{and} \quad \tilde{g}_{H\gamma Z} = 0\,.$$

Generic tensor structure of HVV

$$T^{\mu\nu}(p_1,p_2) = \boxed{\sum_{V=W,Z} \frac{2m_V^2}{v} g^{\mu\nu}} + \boxed{\sum_{V=W,Z,\gamma} \frac{2g}{m_V}\tilde{d}\varepsilon^{\mu\nu\rho\sigma} p_{1\rho}p_{2\sigma}}\,.$$

Only one variable to describe CP-odd

Parametrize amplitude as the sum of SM amplitude and CP-odd one

$$\boxed{\mathcal{M} = \mathcal{M}_{SM} + \tilde{d}\cdot\mathcal{M}_{CP-odd}\,.}$$

The VBF cross section is proportional to the squared matrix element:

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

$$\boxed{OO = \frac{2Re(\mathcal{M}_{SM}^*\mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}}$$

Optimal observable

Optimal observable

Code implemented by HLep group based on `HAWK` (core code written by Fortran)

https://gitlab.cern.ch/Htt2016.developers/HLeptonsCPRW

Input variables (truth-level):

- Higgs boson 4-momentum
- 4-momentum of leading and subleading VBF jets
- Bjorken x1, x2

$$x_{1/2}^{\mathrm{reco}} = \frac{M_{\mathrm{Hjj}}}{\sqrt{s}} e^{\pm y_{\mathrm{Hjj}}}$$

Input variables (reco-level):

- Higgs boson 4-momentum from two decay objects
- 4-momentum of leading and subleading VBF jets
- Bjorken x1, x2 from reconstruction

$$x_1^{\mathrm{reco}} = \frac{M_{\mathrm{final}}}{\sqrt{s}} e^{y_{\mathrm{final}}}$$

$$x_2^{\mathrm{reco}} = \frac{M_{\mathrm{final}}}{\sqrt{s}} e^{-y_{\mathrm{final}}},$$