VBF Higgs CP properties in $H \to \gamma\gamma$ channel at ATLAS(work in progress)

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Introduction

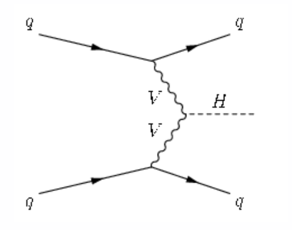
Standard Model Higgs: $J^{PC} = 0^{++}$.

Relevant experiment results in LHC:

- The hypothesis of spin-1 or spin-2 Higgs has been excluded by ATLAS and CMS at >99% CL in $\sqrt{s}$=7&8 TeV, 25fb^{-1} LHC data.
- Pure BSM CP-odd model has been excluded with >96% CL by ATLAS.
- SM+BSM CP-mixing model is under testing. The CL and interval for mixing parameter depend on model.
- All in inclusive Higgs production modes(i.e. gluon fusion dominant).

Vector Boson Fusion(VBF) Higgs production

- Provides a Higgs-Vector Boson vertex and can be sensitive to HVV coupling.
- A good way to find BSM HVV coupling term.



EFT Theory Model and Optimal Observable

Only consider the BSM Higgs-gauge boson interaction, and other interactions are assumed to be as SM predicted, a 6-dimension EFT model is used to provide CP-violating operators:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{f_{\tilde{B}B}}{\Lambda^2}\mathcal{O}_{\tilde{B}B} + \frac{f_{\widetilde{W}W}}{\Lambda^2}\mathcal{O}_{\widetilde{W}W} + \frac{f_{\tilde{B}}}{\Lambda^2}\mathcal{O}_{\tilde{B}} = \mathcal{L}_{SM} + \tilde{g}_{HAA}H\tilde{A}_{\mu\nu}A^{\mu\nu} + \tilde{g}_{HAZ}H\tilde{A}_{\mu\nu}Z^{\mu\nu} + \tilde{g}_{HZZ}H\tilde{Z}_{\mu\nu}Z^{\mu\nu} + \tilde{g}_{HWW}H\widetilde{W}^{+}_{\mu\nu}W^{-\mu\nu}$$

Only 2 $\tilde{g}_{HAA}$ are independent due to constraints imposed by U(1) and SU(2) invariance, so they can be written as:

$$\tilde{g}_{HAA} = \frac{g}{2m_W}(\tilde{d}sin^2\theta_W + \tilde{d}_B cos^2\theta_W),\ \tilde{g}_{HAZ} = \frac{g}{2m_W}sin2\theta_W(\tilde{d} - \tilde{d}_B),$$
$$\tilde{g}_{HZZ} = \frac{g}{2m_W}(\tilde{d}cos^2\theta_W + \tilde{d}_B sin^2\theta_W),\ \tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d}$$

In experiment the contribution from different boson processes can not be distinguished, so we regard $\tilde{d} = \tilde{d}_B$, and use this to represent the VBF Higgs CP mixing. Then the matrix element and its square for VBF is:

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

Only the second term is CP-odd and is a possible source of CP violation in Higgs. A new variable called *Optimal Observable OO* is defined as:

$$OO_1 = \frac{2\Re(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}$$

which is sensitive to $\tilde{d}$. It can be calculated with final state kinematic variables and momentum fraction of initial-state parton from proton.

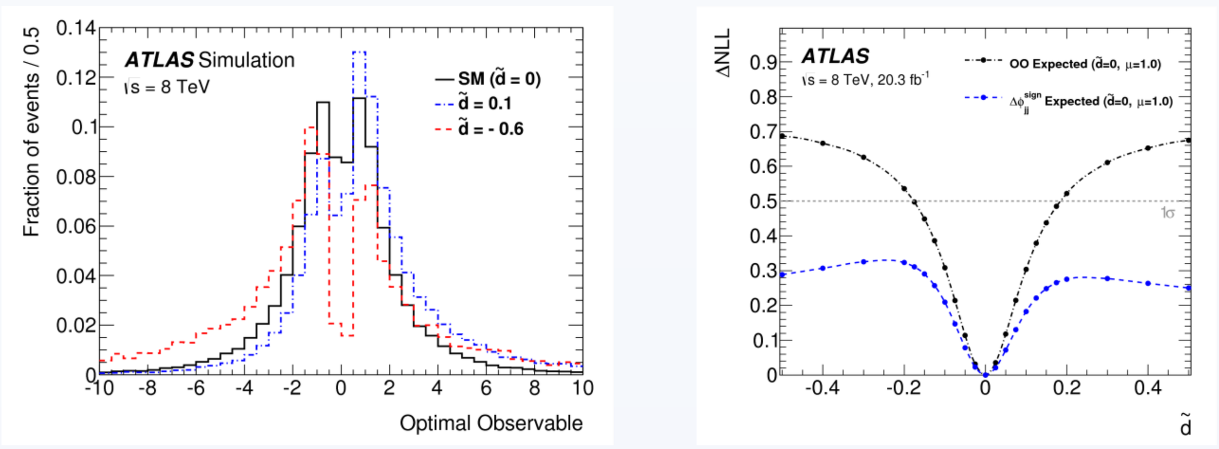


Figure1[1]: Left: Optimal Observable distribution at parton-level for 2 arbitrary $\tilde{d}$ value, after several VBF kinematic cuts.

Right: The comparison of expected ΔNLL curve for new variable OO and tradition CP-testing variable $\Delta\phi_{jj}$ in VBF $H \to \tau\tau$ analysis. It shows OO is more sensitive with Higgs CP.

Data and MC sample

Data(plan to use): full of ATLAS Run2 data, $\sqrt{s}$=13TeV, $\int \mathcal{L}dt$ =140fb^{-1}

Monte Carlo:

- SM VBF signal: Powheg+Pythia8, NNPDF30, VBF Higgs(125GeV) to di-photon channel.
- BSM CP-mixing VBF: matrix element level reweighting method from SM VBF sample $w \equiv \frac{|\mathcal{M}_{CPV}|^2}{|\mathcal{M}_{SM}|^2} = 1 + w_1\tilde{d} + w_2\tilde{d}^2$
- SM resonant background: gluon fusion $H \to \gamma\gamma$, generated with Powheg+Pythia8, ggH125
- SM non-resonant background: Sherpa di-photon final state, $m_{\gamma\gamma} \in [90, 175]$GeV.

Event selection[2]

- Exclude Dalitz events in MC.
- Pass ATLAS trigger match.
- photons should be isolated and pass tight ID requirement.
- At least 2 photons and 2 jets in final state.
- $^{p_T}/_{m_{\gamma\gamma}}$ larger than 0.35 for leading photon, 0.25 for sub-leading photon.
- Di-jet invariant mass m_{jj} lager than 400GeV.
- Jet pseudo-rapidity gap $|\Delta\eta_{jj}| > 2$.
- VBF variable $\eta^{Zepp} = |\eta_{\gamma\gamma} - 0.5 \times (\eta_{j1} - \eta_{j2})| < 5$.

Categorization[2]: Simplified template cross section(STXS) frame work. There are 4 MVA-based categories for VBF-like events: VBF low-p_T^{Hjj} ($p_T^{Hjj} < 25$GeV) BDT tight, loose, VBF high-p_T^{Hjj} ($p_T^{Hjj} > 25$GeV) BDT tight, loose.

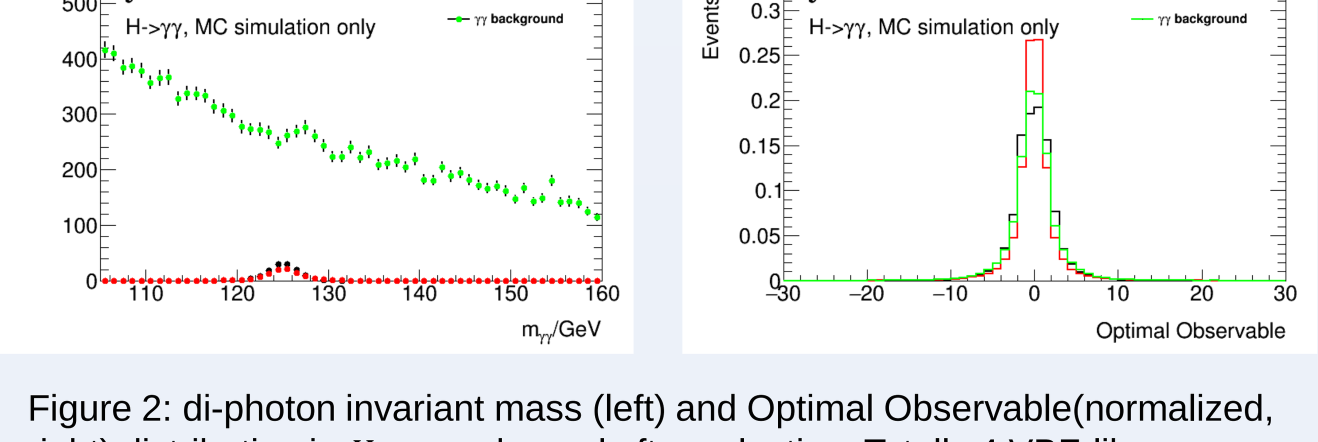


Figure 2: di-photon invariant mass (left) and Optimal Observable(normalized, right) distribution in $H \to \gamma\gamma$ channel after selection. Totally 4 VBF-like categories are used to draw the plot.

	ggF	VBF	Di-photon background	VBF purity
HjjLow_loose	20.82527	42.2653	3198.648	57.96%
HjjLow_tight	5.99863	41.539	381.4368	66.99%
HjjHigh loose	31.82538	10.2294	6176.05	87.38%
HjjHigh tight	33.61908	33.1906	3654.045	24.32%
Total event number	92.2682	127.225	13410.15	49.68%

Table1: Event yields for 3 MC templates in 4 MVA-based categories and the sum, after scaled to 140fb^{-1}. VBF purity is defined as $N_{VBF}/(N_{VBF} + N_{ggF})$ to represent ggF event mixing in VBF categories. The di-photon background yield is estimated with $\mathcal{L} \times \sigma_{\gamma\gamma}/\gamma\gamma\ purity$, i.e. $\gamma j + jj$ event number is considered.

Analysis strategy

Signal-background separation: $m_{\gamma\gamma}$ distribution.

CP test: OO distribution.

Statistical method: likelihood ratio test.

Fitting procedure:

- Fit MC templates to get signal and background $m_{\gamma\gamma}$ model.
  Signal: double-side Crystal Ball. Background: 2nd polynomial exponential PDF.
- Fix the model, fit $m_{\gamma\gamma}$ distribution to get $\hat{\mu}_{VBF}, \hat{N}_{bkg}$. N_{ggF} is fixed to SM value.
- Construct 2-D model with $m_{\gamma\gamma}$ and OO:
  $PDF_{total}(m_{\gamma\gamma}, OO)$
  $= \hat{\mu}_{VBF} \times N^{SM}_{VBF} \times f_{sig}(m_{\gamma\gamma}) \times g_{VBF}(OO) + N^{SM}_{ggF} \times f_{sig}(m_{\gamma\gamma}) \times g_{ggF}(OO)$
  $+ \hat{N}_{bkg} \times f_{sig}(m_{\gamma\gamma}) \times g_{ggF}(OO)$
- Calculate the Negative Log Likelihood(NLL) and $\Delta\text{NLL} \equiv NLL - NLL_{min}$ with $PDF_{total}(m_{\gamma\gamma}, OO)$ and data for each $\tilde{d}$ (SM Asimov data now, for expect result).

Above procedure is performed in both pre-selection and MVA category combination level.

The approximate central confidence interval at 68%(95%) CL could be extracted from ΔNLL curve.

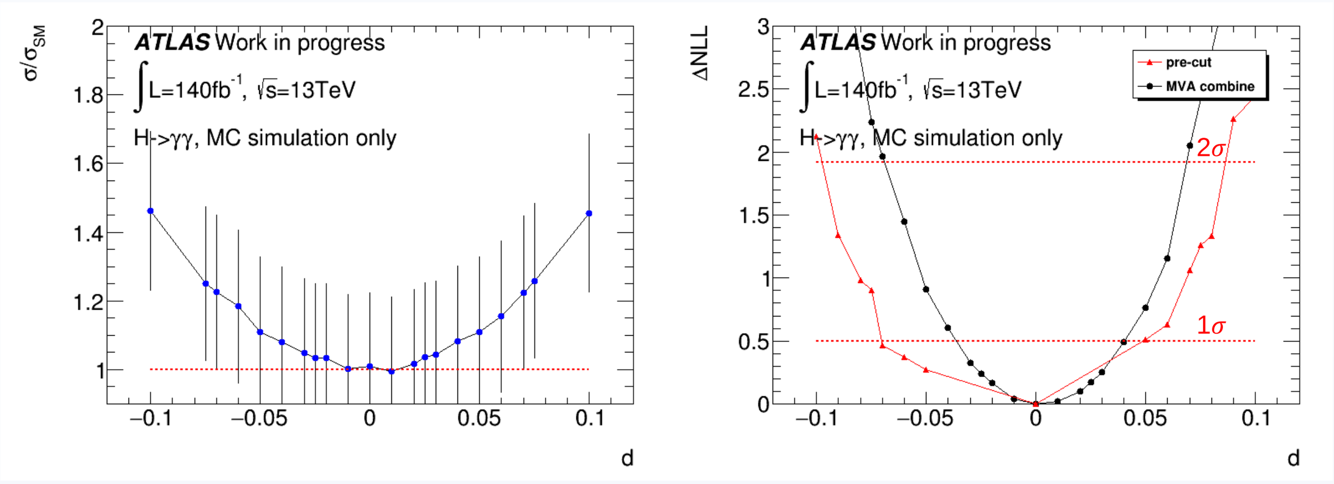


Figure 3: Best fit VBF signal strength with 4 combined MVA categories(left) and ΔNLL curve for different $\tilde{d}$ values.

Preliminary Result

Only considering the statistic uncertainty, we can have a preliminary expected result:

- With cut-based method, the CP-mixing parameter $\tilde{d}$ is constrained to the interval [-0.07, 0.05] @ 68% CL, and [-0.10, 0.09] @ 95% CL.
- After the combination of 4 MVA categories, the interval could be narrowed down to [-0.04, 0.04] @ 68% CL, and [-0.07, 0.07] @ 95% CL.

Conclusion and next-step

Previous research in VBF Higgs CP is performed in $H \to \tau\tau$ channel with 36.1fb^{-1} ATLAS data and announced in ICHEP2019[3], giving the observed $\tilde{d}$ constraint [-0.09, 0.035] @ 68% CL, and no constraints in 95% CL. We expect a most precise VBF Higgs CP mixing measurement can be provided after finishing current work.

Next step:

- Data-MC comparison, use side-band data to model the background.
- Develop other methods to get purest VBF events and have better $\tilde{d}$ constraints.
- Introduce systematic uncertainty.

Reference

[1] ATLAS Collaboration, Test of CP invariance in vector-boson fusion production of the Higgs boson using the Optimal Observable method in the ditau decay channel with the ATLAS detector, Eur. Phys. J. C 76 (2016) 658, arXiv: 1602.04516 [hep-ex]

[2] ATLAS Collaboration, Measurements of Higgs boson properties in the diphoton decay channel with 36 fb−1 of pp collision data at √ s = 13 TeV with the ATLAS detector, Phys. Rev. D 98 (2018) 052005, arXiv: 1802.04146 [hep-ex]

[3]ATLAS Collaboration, Test of CP invariance in vector-boson fusion production of the Higgs boson in the $H \to \tau\tau$ channel in proton-proton collisions at √ s = 13 TeV with the ATLAS detector, ATLAS-CONF-2019-050

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