Measurements on Higgs boson width and anomalous couplings with on-shell and off-shell production in ZZ decay channel at CMS

Hanwen Wang
Beihang University & Universite Libre de Bruxelles

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Outline

Current status of Γ_H measurement

- At LHC, resolution limits direct measurement to O(1) GeV
- We can use off-shell production to set a more strict limit on total width of Higgs

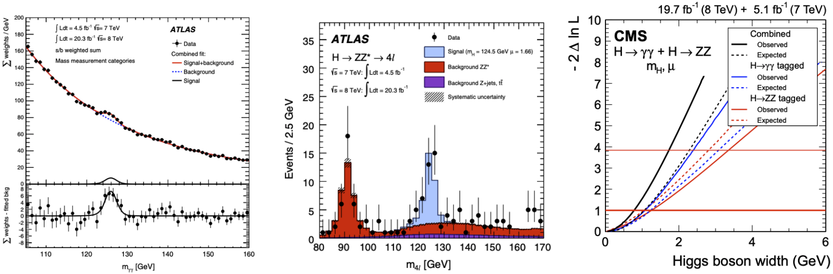

Figure 1: Direct width measurements from ATLAS and CMS

EPJ C 75 (2015) 212 [1]
Phys. Rev. D 90(2014) 052004 [2]

Off-shell Higgs production

- A significant enhancement in the off-shell Higgs production rate exists. [3]
- Interference between the two processes, off-shell Higgs production and $gg \to VV$ continuum background, is sizable and negative in SM [5]
- Off-shell Higgs production is necessary to preserve unitarity, and one of the goals of off-shell analysis is to examine that there is non-zero, negative interference between the signal and the background.

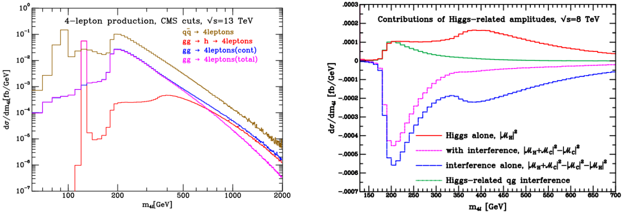

Figure 2: Considering signal and background interference John M. Campbell. [5]

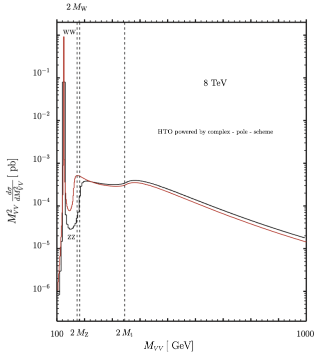

Figure 3: The distributions of m_{VV} in the gluon-gluon fusion production modes Kauer, Passarino (JHEP 08 (2012))[3]

BSM anomalous HVV interactions

- The signal scattering amplitude describing the interaction between a spin-zero H boson and two spin-one gauge bosons VV is written as

$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} - \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{V}} q_2^2}{(\Lambda_1^{\mathrm{VV}})^2} - \frac{\kappa_3^{\mathrm{VV}} (q_1 + q_2)^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

- Any anomalous coupling can be described with an effective on-shell cross sectional fraction and a phase

$$f_{\mathrm{ai}} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j} \qquad \phi_{\mathrm{ai}} = \tan^{-1}(a_i/a_1)$$

- $f_{\Lambda \mathrm{Q}}$ observable only from off-shell. Others can be measured from either on-shell or off-shell.

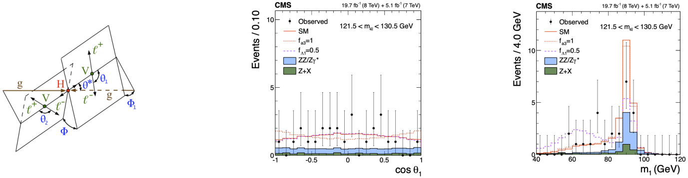

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Figure 4: Illustration of the production and decay of the Higgs boson(left), distribution of cos_{θ_1} (middle) and m_1 (right) from ggH

Higgs width measurement

- $\sigma_{\text{offshell}} \sim \mathbf{g}_{\mathrm{g}}^2\mathbf{g}_{\mathrm{V}}^2$ and doesn't depend on total width Γ_{H} as σ_{onshell} does
- $\frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell},\ SM}} = \mu_{\text{off-shell}} = \kappa^2_{g,\ \text{off-shell}} \cdot \kappa^2_{V,\ \text{off-shell}}$
- $\frac{\sigma^{gg\to H\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ}_{\text{on-shell},\ SM}} = \mu_{\text{on-shell}} = \frac{\kappa^2_{g,\ \text{on-shell}} \cdot \kappa^2_{V,\ \text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$
- Assuming the on-peak and off-peak couplings are the same, we can reinterpret the limit on μ_{offshell}, combined with μ_{onshell} measurement, as a limit on Γ_{H}
- When we also allow BSM HVV couplings a_i, similar on-shell and off-shell relationship holds, and the differences in kinematics (including m_{4l}) are taken into account.

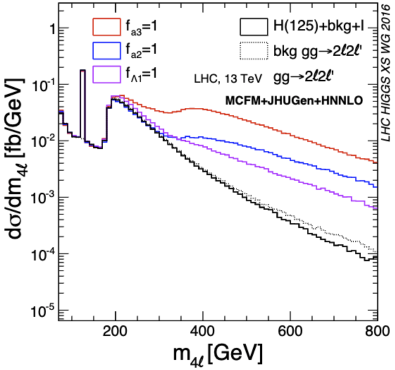

Figure 5: Distribution of m_{4l}, YR4[4]

Analysis strategy

- This analysis use both on-shell and off-shell events in the $H \to ZZ \to 4l$ channel
- Perform an unbinned extended maximum likelihood fit to the events split into different categories

- Each event has an associated likelihood describing the probability it belongs to signal, background, or interference:

$$\mathcal{L}_i = N_{\mathrm{gg}\to\mathrm{ZZ}} \left[\mu\Gamma \times \mathcal{P}^{gg}_{\mathrm{sig}} + \sqrt{\mu\Gamma} \times \mathcal{P}^{gg}_{\mathrm{int}} + \mathcal{P}^{gg}_{\mathrm{bkg}}\right] + N_{\mathrm{VBF}} \left[\mu\Gamma \times \mathcal{P}^{VBF}_{\mathrm{sig}} + \sqrt{\mu\Gamma} \times \mathcal{P}^{VBF}_{\mathrm{int}} + \mathcal{P}^{VBF}_{\mathrm{bkg}}\right] + N_{\mathrm{q\bar{q}ZZ}} \mathcal{P}^{q\bar{q}}_{\mathrm{bkg}} + N_{\mathrm{ZX}} \mathcal{P}^{ZX}_{\mathrm{bkg}}$$

where P is the normalized probability distribution for each process

- Matrix element techniques are utilized to combine kinematic information from the decay particles and the associated jets to identify the production mechanism and increase sensitivity to the anomalous couplings.

Event reconstruction and selection

- Loose electron (muon) :
  - Loose electrons passing selections
  - $p_{\mathrm{T}} > 7(5)$GeV;
  - $|\eta| < 2.5(2.4)$;
  - vertex cut $d_{xy} < 0.5cm$; $d_z < 1cm$;
  - $\mathrm{SIP}_{3D} < 3$;
  - BDT Selections ($RelPFIso(\Delta R = 0.3) < 0.35$);
- Z candidate
  - Any OS-SF pair that satisfy $12 < m_{ll(\gamma)} < 120$ GeV
- Build all possible ZZ candidates defined as pairs of non-overlapping Z candidate; define Z_1 candidate with $m_{ll(\gamma)}$ closest to the POG m_Z mass
  - $m_{Z\,1} > 40$GeV; $p_{\mathrm{T}}(l1) > 20$GeV; $p_{\mathrm{T}}(l2) > 10$GeV
  - $\Delta R > 0.02$ between each of the four leptons;
  - $m_{ll} > 4$GeV for OS pairs (regardless of flavour);
  - Reject 4μ and 4 e candidates where the alternative pair $\mathrm{Z_a Z_b}$ satisfies $|m_{Z_\alpha} - m_Z| <| m_{Z_1} - m_Z |$ and $m_{Z_b} < 12$GeV
  - $m_{4l} > 70$GeV
- If more than one ZZ candidate is left, choose the one of highest $\mathcal{D}^{kin}_{bkg}$.
- If $\mathcal{D}^{kin}_{bkg}$ is the same, take the one with $\mathrm{Z_1}$ mass closest to $\mathrm{m_Z}$

Event yields

SM, on-shell

	VBF-tagged	VH-tagged	Untagged
VBF signal	4.7 (3.4)	0.3 (0.2)	5.7 (0.8)
ZH signal	0.2 (0.4)	0.5 (1.0)	1.5 (2.5)
WH signal	0.3 (0.6)	0.7 (1.9)	2.1 (5.3)
$gg \to H$ signal	5.5 (5.8)	3.2 (3.3)	98.9 (98.4)
$t\bar{t}H$ signal	0.2 (0.2)	0.1 (0.1)	1.1 (1.2)
$b\bar{b}H$ signal	0.1 (0.1)	0.1 (0.1)	1.1 (1.1)
VV bkg.	0.2	0.1	0.5
gg bkg.	0.8	0.3	12.7
$q\bar{q} \to 4\ell$ bkg.	1.6	1.5	120.3
Z+X bkg.	5.2	3.0	46.3
Total expected	18.8	9.7	290.3
Total observed	19	9	332

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SM, off-shell

	VBF-tagged	VH-tagged	Untagged
VV $s+b+i$	6.4 (9.4)	2.8 (3.1)	17.1 (14.6)
gg $s+b+i$	9.8 (15.4)	8.2 (9.8)	231.8 (224.7)
$q\bar{q} \to 4\ell$ bkg.	15.8 (33.5)	27.7 (31.2)	992.0 (970.8)
Z+X bkg.	2.4 (6.4)	2.8 (3.3)	45.4 (40.8)
Total expected	34.4 (64.8)	41.6 (47.5)	1286.3 (1251.0)
Total observed	36 (92)	46 (51)	1325 (1264)

Results

Results from A. M. Sirunyan et al. [6]

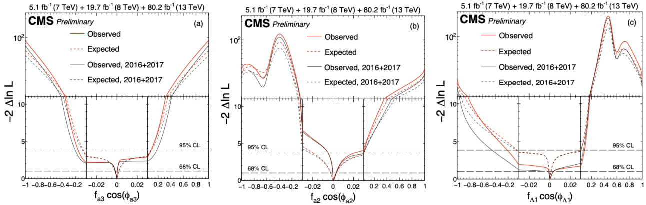

Figure 6: Observed (solid) and expected (dashed) likelihood scans of $f_{a3}\cos(\phi_{a3})$ (left), $f_{a2}\cos(\phi_{a2})$ (middle), $f_{\Lambda1}\cos(\phi_{\Lambda1})$ (right)

Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.0000^{+0.0005}_{-0.0011}$ $[-0.0067, 0.0050]$	$0.0000^{+0.0014}_{-0.0014}$ $[-0.0098, 0.0098]$
$f_{a2}\cos(\phi_{a2})$	$0.0005^{+0.0025}_{-0.0008}$ $[-0.0029, 0.0129]$	$0.0000^{+0.0011}_{-0.0017}$ $[-0.0100, 0.0117]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.0001^{+0.0020}_{-0.0010}$ $[-0.0150, 0.0501]$	$0.0000^{+0.0010}_{-0.0010}$ $[-0.0152, 0.0158]$

Summary of allowed 68% CL (central values with uncertainties) and 95% CL (in square brackets) intervals on the anomalous coupling parameters $f_{ai}\cos(\phi_{ai})$,Run 2 (on-shell and off-shell) and Run 1 (on-shell only) combined

Results

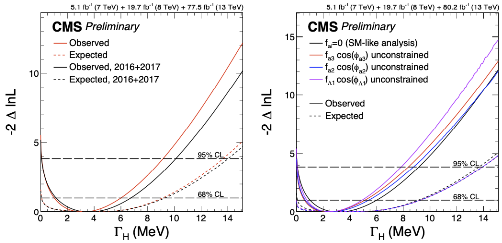

Figure 7: Observed (solid) and expected (dashed) likelihood scans of Γ_H. Observed (solid) and expected (dashed) likelihood scans of Γ_H. Left plot: Results of analysis of the data from 2016 and 2017 only (black) and the combined Run 1 and Run 2 analysis (red) are shown for the SM-like couplings. Right plot: Results of analysis of the data from the combined Run 1 and Run 2 analyses for the SM-like couplings and with three anomalous coupling parameters of interest unconstrained

Parameter	Observed	Expected
Γ_H (MeV)	$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]	$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]

The total width Γ_H measurement, showing allowed 68% CL (central values with uncertainties) and 95% CL (in square brackets) Results from A. M. Sirunyan et al. [6]

Summary

- Studies of on-shell and off-shell Higgs boson production in the ZZ to four-lepton final state are presented, using data from the CMS experiment at the LHC that corresponds to an integrated luminosity of $80.2 fb^{-1}$ at 13 TeV.

- $\Gamma_H < 9.16$ MeV at 95% CL, compared with Run-1 results $\Gamma_H <$ 22 MeV [7] at 95% CL (expected: $\Gamma_H < 13.7$ MeV at 95% CL, Run-1 $\Gamma_H < 33$ MeV)

- limits on BSM anomalous couplings parameters $f_{ai} cos(\phi_{ai})$ improve by 10^2 to 10^3 compared to Run-1. $f_{a3} < 0.008$ at 95% CL while $f_{a3} < 0.4$ [8] from Run-1 results

- Results of full Run-2 data, combining with ZZ to $2l2\nu$ off-shell analysis, are being examined inside the CMS collaboration and are expected to go public soon.

References I

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