Higgs Signal-Background Interference in gg $\rightarrow$ VV in the Standard Model and Beyond

Claire O'Brien
Royal Holloway University of London

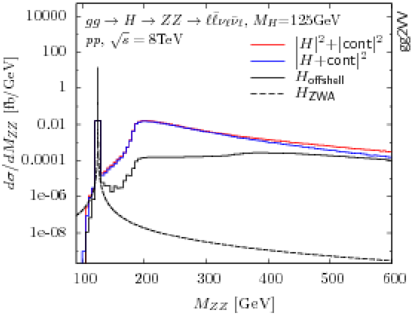
In collaboration with Dr Nikolas Kauer and Dr Eleni Vryonidou

(arxiv 1502.04113)

29th April 2015

Motivation

- NWA not suitable for $H \to VV$ (Kauer & Passarino, arxiv 1206.4803). Threshold effects are visible, e.g. at $\sim 2m_V$ there is a bump in the invariant mass distribution.



- Signal has larger impact in off-shell region than previously thought, so signal/background interference becomes more important.

Motivation

- Off-shell and interference effects open up some good opportunities, e.g. chance to perform (model-independent?) indirect measurement of the Higgs width via comparison of on-shell/off-shell signals - dependance on coupling rescalings drops out (Caola & Melnikov arxiv:1307.4935, CMS arxiv:1405.4121).
- Changes in line shape in differential distributions due to interference may give early hints of new physics.
- **New: studies of interference in gg $\rightarrow$ VV $\rightarrow$ 2l2q/lν2q (SM) and gg $\rightarrow$ VV $\rightarrow$ 4l/2l2ν (Higgs singlet model).**

Interference

- Cross Section $\propto$ matrix element squared:

$$|\mathcal{M}|^2 = |\mathcal{M}_{signal}|^2 + |\mathcal{M}_{continuum}|^2 + \mathbf{2Re}\left(\mathcal{M}^*_{\mathbf{signal}}\mathcal{M}_{\mathbf{continuum}}\right)$$

- Coherent processes with the same initial and final states can interfere
- Interference often not treated carefully, considered correction or part of error.
- Can affect size of signal/background and shape of kinematic differential distributions.

Semileptonic Processes

We are interested in the semi-leptonic decays of the Higgs Boson:

- gg $\to H \to W\,(\to l\nu_l)\,W\,(\to q\bar{q}')$
- gg $\to H \to Z\,(\to l^+l^-)\,Z\,(\to q\bar{q})$
- Advantage: large branching fraction, particularly for high Higgs mass. Only one neutrino (or none in ZZ case), so mass reconstruction possible.
- Disadvantage: huge QCD background (Vector Boson + 2 jets)
- Dominant background is tree level, signal process is one loop.

Signal vs. Background

- In both channels, can use selective cuts to enhance signal to background
- Kinematically, since $m_H < 2m_V$, only one vector boson in the signal process can be on-shell, equally probable.
- Background tree level processes have only one boson, the leptonically decaying one, typically on-shell.
- If we make cuts to require that the hadronic boson be the on-shell one, can improve signal to background ratio significantly.

Cuts

Cuts:

- minimal cuts avoiding numerical instabilities and soft photon singularities: $M_{Z/\gamma} > 4$ GeV, $p_T(V) > 1$ GeV.
- 'LHC' cuts: typical detector cuts in addition to the minimal cuts: $|\eta(l)| < 2.5$, $|\eta(j)| < 4.5$, $p_{Tj} > 25$ GeV, $p_{Tl} > 20$ GeV.
- background suppression cuts for a 400 GeV Higgs, as used by ATLAS: in addition to the LHC cuts, $|\eta(j)| < 2.8$, $p_{Tj2} > 40$ GeV, $p_{Tj1} > 60$ GeV, $|M_{jj} - M_V| < 5\Gamma_V$ and $\Delta(R)_{jj} < 1.3$.

For the two WW cases, we also calculate results using background suppression cuts for a 125.5 GeV Higgs at $\sqrt{s} = 14$ TeV:

- $p_{TV} > 1$ GeV, $E_{T,miss} < 40$ GeV, $|\eta(l)| < 2.5$, $|\eta(j)| < 5$, $p_{Tj1} > 30$ GeV, $p_{Tj2} > 20$ GeV, 65 GeV $< M_{jj} <$ 95 GeV, $M_{lv} < 45$ GeV, $M_{lvjj} < 130$ GeV, $\Delta(R)_{jl} > 0.2$, and $M_{l\nu} < 45$ GeV.

Results: Notation

Notation:

$$S \sim |\mathcal{M}_{signal}|^2 \quad (1)$$

$$I_{tree} \sim 2\,\mathrm{Re}(\mathcal{M}^*_{signal}\,\mathcal{M}_{tree}) \quad (2)$$

$$I_{loop} \sim 2\,\mathrm{Re}(\mathcal{M}^*_{signal}\,\mathcal{M}_{loop}) \quad (3)$$

$$I_{full} \sim 2\,\mathrm{Re}(\mathcal{M}^*_{signal}\,\mathcal{M}_{background}) \quad (4)$$

$$R_i = \frac{S + I_i}{S}. \quad (5)$$

Results: $gg \to H \to W^+W^- \to \bar{\ell}\nu_\ell \bar{q}_u q_d$

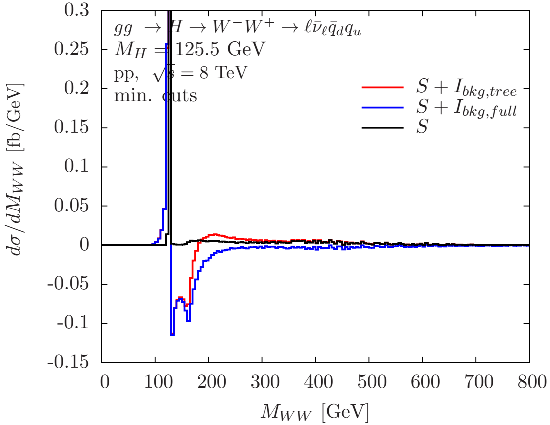
$gg \to H \to W^+W^- \to \bar{\ell}\nu_\ell \bar{q}_u q_d$ σ [fb], pp, $\sqrt{s} = 8$ TeV		interference			ratio		
cuts	S	I_{tree}	I_{loop}	I_{full}	R_{tree}	R_{loop}	R_{full}
min.	67.28(9)	-2.47(2)	-4.99(1)	-7.48(9)	0.963(2)	0.926(2)	0.889(3)
LHC	1.978(6)	0.266(4)	-2.647(6)	-2.38(3)	1.135(5)	-0.338(4)	-0.20(2)
bkg.	13.30(2)	-0.0054(2)	-1.052(5)	-1.058(4)	1.000(2)	0.921(2)	0.920(2)

Integrated cross sections for the process $gg \to H \to W^+W^- \to \bar{\ell}\nu_\ell \bar{q}_u q_d$ at $\sqrt{s} = 8$ TeV with minimal and LHC cuts for a 125.5 GeV Higgs and background suppression cuts for a 400 GeV Higgs.

$gg \to H \to W^+W^- \to \bar{\ell}\nu_\ell \bar{q}_u q_d$ σ [fb], pp, $\sqrt{s} = 14$ TeV		interference			ratio		
cuts	S	I_{tree}	I_{loop}	I_{full}	R_{tree}	R_{loop}	R_{full}
bkg.	47.45(5)	-0.0163(7)	0.0298(2)	0.0133(6)	1.000(2)	1.001(2)	1.000(2)

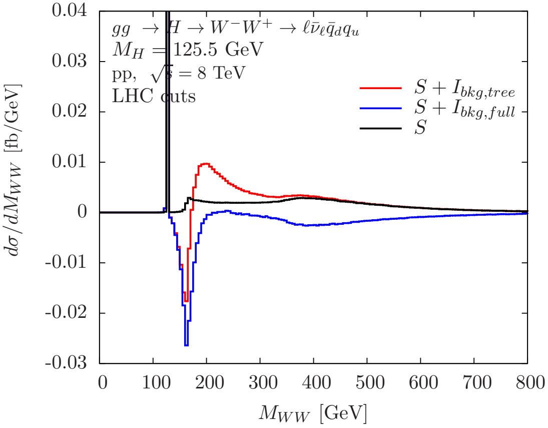
Integrated cross sections for the process $gg \to H \to W^+W^- \to \bar{\ell}\nu_\ell \bar{q}_u q_d$ with $\sqrt{s} = 14$ TeV and background suppression cuts for a 125.5 GeV Higgs.

Results: $gg \to H \to W^+W^- \to \bar{\ell}\nu_\ell \bar{q}_u q_d$, Minimal Cuts



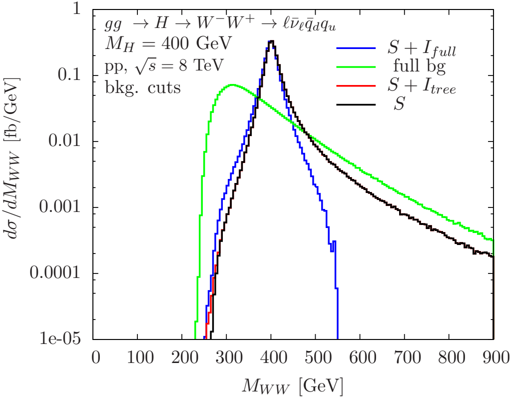
Invariant mass distribution for the process $gg \to H \to W^-W^+ \to \ell\bar{\nu}_\ell q_u \bar{q}_d$ with minimal cuts: $p_t(W) > 1$GeV.

Results: $gg \to H \to W^+W^- \to \bar{\ell}\nu_\ell\bar{q}_u q_d$, LHC Cuts



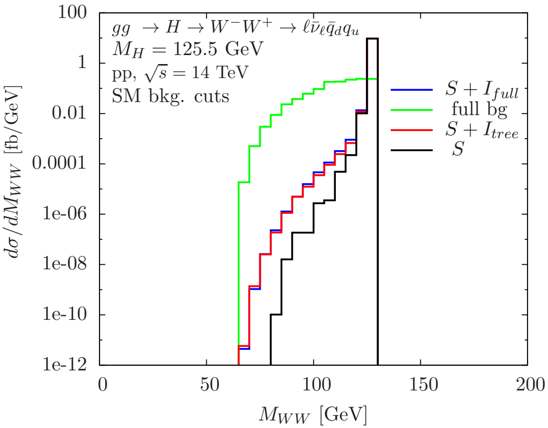
Invariant mass distribution for the process $gg \to H \to W^-W^+ \to \ell\bar{\nu}_\ell q_u\bar{q}_d$ with LHC cuts: in addition to minimal cuts, $p_T(j) > 25$ GeV, $p_t(l) > 20$ GeV, $|\eta_j| < 4.5$, $|\eta_l| < 2.5$.

Results: $gg \to H \to W^+W^- \to \bar{\ell}\nu_\ell\bar{q}_u q_d$, BG Suppression Cuts



Invariant mass distribution for the process $gg \to H \to W^-W^+ \to \ell\bar{\nu}_\ell q_u\bar{q}_d$ with a 400 GeV Higgs and background suppression cuts: in addition to the LHC cuts, $p_T(j1) > 60$ GeV, $p_T(j2) > 40$ GeV, $|\eta(j)| < 2.8, \Delta(R)_{jj} < 1.3$, and $|M_{jj} - M_W| < 5\Gamma_W$.

Results: $gg \to H \to W^+W^- \to \bar{\ell}\nu_\ell \bar{q}_u q_d$, BG Suppression Cuts



Invariant mass distribution for the process $gg \to H \to W^+W^- \to \ell\bar{\nu}_\ell q_u\bar{q}_d$ with background suppression cuts for a 125.5 GeV Higgs at $\sqrt{s} = 14$ TeV.

The Higgs Singlet Model

Before symmetry breaking:

$$\begin{aligned} V = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2 + \frac{1}{2}M^2 s^2 + \lambda_1 s^4 \\ + \lambda_2 s^2\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right) + \mu_1 s^3 + \mu_2 s\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right) \end{aligned} \quad (6)$$

- s is a new scalar field, a singlet under all the gauge groups of the SM.
- In the unitary gauge, we write the Higgs doublet as

$$\Phi = \begin{pmatrix} 0 \\ \frac{(\phi+v)}{\sqrt{2}} \end{pmatrix} \quad (7)$$

- we can define a mixing angle $\tan(2\theta) = \frac{-\mu_2\nu}{\lambda\nu^2 - \frac{1}{2}M^2}$. giving

$$\begin{aligned} h_1 &= \phi\cos(\theta) - s\sin(\theta) \\ h_2 &= \phi\sin(\theta) + s\cos(\theta) \end{aligned} \quad (8)$$

The Higgs Singlet Model

- Note that since the new field only couples to Φ, if we rewrite $\phi = h_1 \cos(\theta) + h_2 \sin(\theta)$ and take h_1 as the discovered resonance with a mass of 125 GeV, and $m_{h2} > m_{h1}$, standard model higgs processes will be modified by a constant coupling factor of $\cos(\theta)$ for the lighter particle and $\sin(\theta)$ for the new heavy particle.
- After symmetry breaking:

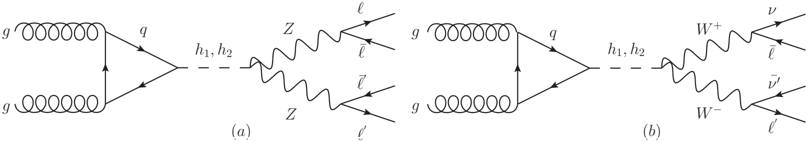
$$V = \frac{\lambda}{4}\phi^4 + \lambda\nu^2\phi^2 + \lambda\nu\phi^3 + \frac{1}{2}M^2 s^2 + \lambda_1 s^4 + \frac{\lambda_2}{2}\phi^2 s^2 + \lambda_2\nu\phi s^2 + \mu_1 s^3 + \frac{\mu_2}{2}\phi^2 s + \mu_2\nu\phi s. \tag{9}$$

Processes

- We are interested in the fully leptonic decays:

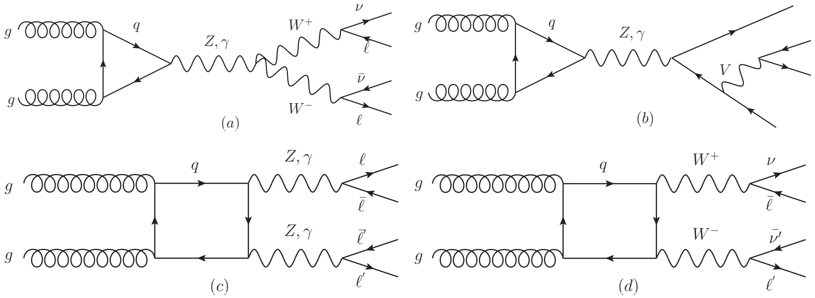
$$gg \to h_1/h_2 \to ZZ \to 4l$$

$$gg \to h_1/h_2 \to W^+W^- \to l\bar{\nu}_l\bar{l}\nu$$



- $ZZ \to 4l$ considered the 'golden mode', fully reconstructible. Well studied process.
- WW has higher rate, but harder to analyse due to two neutrinos.

Background Diagrams



Continuum diagrams that can interfere.

Calculation

gg2VV: Leading order event generation and parton level cross sections and differential distributions available.

- New version with Higgs singlet extension available, and multi-channel mapping implemented for phasespace integration.
- Model generated using Feynrules 2.0 (Christensen, Duhr et al.), produces FeynArts model file.
- Feynarts+Formcalc (Hahn et al.) used to generate amplitudes, adapted for compatibility with gg2VV
- Fixed or variable scales, different propagator schemes, modified couplings available.
- All SM $gg \to VV \to$4 lepton final states previously available, Higgs singlet $gg \to WW/ZZ \to 2\ell 2\ell' / 2\ell 2\nu$ in new version and SM $gg \to WW/ZZ \to 2l2q$ coming soon.

Results: WW, Minimal Cuts

$gg \to h_2 \to W^- W^+ \to \ell\bar{\nu}\bar{\ell}'\nu'$ min. cuts σ [fb], pp, $\sqrt{s}=8$ TeV		interference			ratio		
M_{h2} [GeV]	S	I_{h1}	I_{bkg}	I_{full}	R_{h1}	R_{bkg}	R_{full}
300	1.414(2)	0.1173(6)	–0.045(1)	0.072(2)	1.083(2)	0.968(2)	1.051(2)
600	0.1874(2)	–0.0558(3)	0.0942(3)	0.0385(4)	0.702(2)	1.503(2)	1.205(3)
900	0.01799(2)	–0.03500(6)	0.04957(7)	0.01458(9)	–0.945(4)	3.755(5)	1.810(6)

Integrated cross sections for the process $gg \to (h1/h2) \to WW \to \ell\bar{\nu}\bar{\ell}'\nu'$ with $m_{h2} = 300, 600, 900$ GeV and minimal cuts ($p_t(V) > 1$ GeV) for $\theta = \frac{\pi}{8}$. The integration error is given in brackets.

$gg \to h_2 \to W^- W^+ \to \ell\bar{\nu}\bar{\ell}'\nu'$ min. cuts σ [fb], pp, $\sqrt{s}=8$ TeV		interference			ratio		
M_{h2} [GeV]	S	I_{h1}	I_{bkg}	I_{full}	R_{h1}	R_{bkg}	R_{full}
300	0.3878(6)	0.0389(4)	-0.0133(3)	0.0256(5)	1.100(3)	0.966(3)	1.066(3)
600	0.05379(8)	-0.0194(2)	0.0289(3)	0.0095(3)	0.639(4)	1.538(6)	1.176(6)
900	0.005129(8)	-0.01229(5)	0.01519(7)	0.00290(8)	-1.396(9)	3.96(2)	1.57(2)

Integrated cross sections for the process $gg \to (h1/h2) \to WW \to \ell\bar{\nu}\bar{\ell}'\nu'$ with $m_{h2} = 300, 600, 900$ GeV and minimal cuts ($p_t(V) > 1$ GeV) for $\theta = \frac{\pi}{15}$. The integration error is given in brackets.

Results: WW, Window Cuts

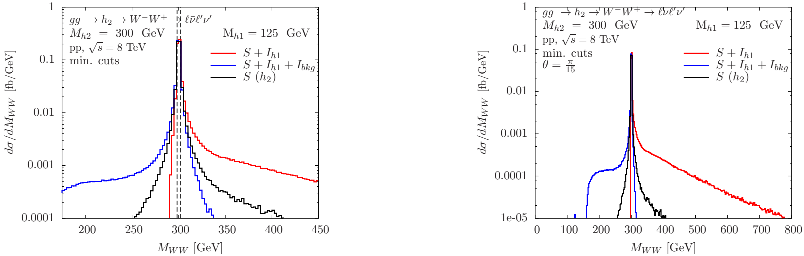
$gg \to h_2 \to W^- W^+ \to \ell\bar{\nu}\bar{\ell}'\nu'$ min. cuts & $\lvert M_{VV} - M_{h2}\rvert < \Gamma_{h2}$ σ [fb], pp, $\sqrt{s} = 8$ TeV		interference			ratio		
M_{h2} [GeV]	S	I_{h1}	I_{bkg}	I_{full}	R_{h1}	R_{bkg}	R_{full}
300	0.990(1)	0.00033(8)	0.0343(2)	0.0346(2)	1.000(2)	1.035(2)	1.035(2)
600	0.1360(2)	–0.00183(5)	0.01584(7)	0.01401(8)	0.987(2)	1.116(2)	1.103(2)
900	0.01292(2)	–0.00134(1)	0.00432(5)	0.00298(5)	0.896(2)	1.334(4)	1.230(4)

Integrated cross sections for the process $gg \to (h1/h2) \to WW \to \ell\bar{\nu}\bar{\ell}'\nu'$ with $m_{h2} = 300, 600, 900$ GeV with minimal cuts and a window cut of $\lvert M_{WW} - M_{h2}\rvert < \Gamma_{h2}$. $\theta = \frac{\pi}{8}$.

$gg \to h_2 \to W^- W^+ \to \ell\bar{\nu}\bar{\ell}'\nu'$ min. cuts & $\lvert M_{VV} - M_{h2}\rvert < \Gamma_{h2}$ σ [fb], pp, $\sqrt{s} = 8$ TeV		interference			ratio		
M_{h2} [GeV]	S	I_{h1}	I_{bkg}	I_{full}	R_{h1}	R_{bkg}	R_{full}
300	0.2728(5)	3(2)e-05	0.0101(2)	0.0101(2)	1.000(3)	1.037(3)	1.037(3)
600	0.03827(7)	-0.00018(3)	0.00424(5)	0.00405(6)	0.995(3)	1.111(3)	1.106(3)
900	0.003634(7)	-0.000134(6)	0.000931(9)	0.00080(2)	0.963(3)	1.256(4)	1.219(5)

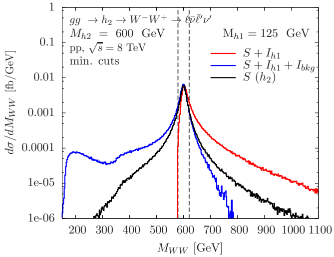
Integrated cross sections for the process $gg \to (h1/h2) \to WW \to \ell\bar{\nu}\bar{\ell}'\nu'$ with $m_{h2} = 300, 600, 900$ GeV with minimal cuts and a window cut of $\lvert M_{WW} - M_{h2}\rvert < \Gamma_{h2}$. $\theta = \frac{\pi}{15}$.

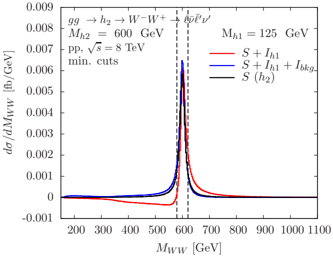
Results: WW, $M_{h2} = 300$ GeV



Invariant mass distributions for $gg \to (h1/h2) \to WW \to \ell\bar{\nu}\bar{\ell}'\nu'$ with $m_{h2} = 300$ GeV and minimal cuts for $\theta = \frac{\pi}{8}$ (left) and $\theta = \frac{\pi}{15}$(right).

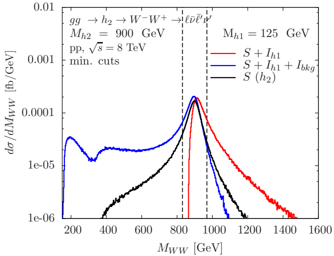
Results: WW, $M_{h2} = 600$ GeV

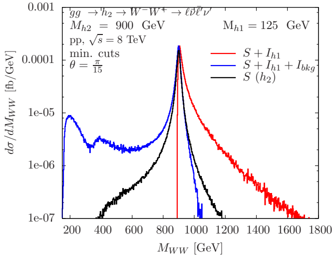




Invariant mass distributions for $gg \to (h1/h2) \to WW \to \ell\bar{\nu}\bar{\ell}'\nu'$ with $m_{h2} = 600$ GeV and minimal cuts (both $\theta = \frac{\pi}{8}$).

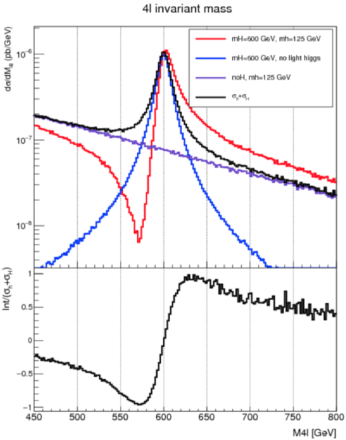
Results: WW, $M_{h2} = 900$ GeV





Invariant mass distributions for $gg \to (h1/h2) \to WW \to \ell\bar{\nu}\bar{\ell}'\nu'$ with $m_{h2} = 900$ GeV and minimal cuts for $\theta = \frac{\pi}{8}$ (left) and $\theta = \frac{\pi}{15}(right)$.

Other Studies



from arxiv 1501.02139, Maina - study of heavy-light Higgs interference in EWS model with additional Z_2 symmetry. See also: Englert, Low & Spannowsky, arxiv 1502.04678. Study dependence of interference on width and propagator scheme choice for gg$\rightarrow h_1/h_2 \rightarrow ZZ$.

Conclusions

- Interference effects need a more careful treatment than previously given.
- Effects clear in lineshape of differential distribution. May be enhanced or reduced with selection cuts.
- Semileptonic Decays: Strong effects away from resonance peak, but largest contribution is from signal-continuum background rather than signal-tree.
- Heavy Higgs: Largest impact for higher mass particles (larger width), and away from resonance peaks.