Off-Shell Higgs Production and Higgs Interference at the LHC

Nikolas Kauer

Royal Holloway, University of London

LHCHXSWG YR4 section in collaboration with F. Caola, Y. Gao, L. Soffi, J. Wang and 28 other contributors

arXiv:1506.01694 in collaboration with C. O'Brien and E. Vryonidou

arXiv:1502.04113 in collaboration with C. O'Brien

arXiv:1206.4803 in collaboration with G. Passarino

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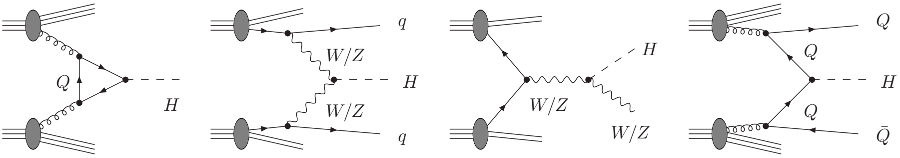
Outline

- $H \to ZZ, WW$ in ggF & VBF: sizeable off-shell Higgs signal contribution with large signal-backg. interference
- $H \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ and $ZZ \to 4\ell$ interference in ggF
- Interference effects for semileptonic decay modes
- Interference for $pp \to H \to ZZ$ + jet
- Precision predictions for $gg\ (\to H) \to VV$ interference/bkg.
- Higgs width measurement in a nutshell
- Off-shell Higgs boson signal strength & novel Higgs width bound
- BSM/EFT: exploiting the off-shell $H \to VV$ region
- BSM: model dependence of the off-shell Higgs width bound
- Higgs width constraints from $gg \to H \to \gamma\gamma$
- BSM: heavy Higgs-light Higgs-bkg. interference effects
- High-mass $H \to VV$ signal at a linear collider
- LHCHXSWG YR4: Off-shell Higgs and Higgs interference
- Summary

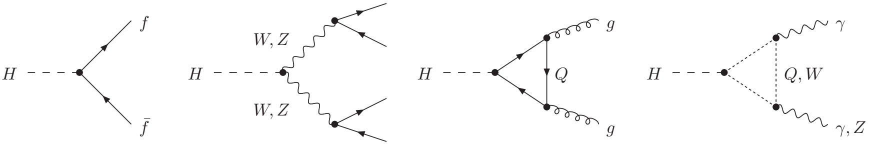
SM Higgs boson production and decay at the Large Hadron Collider (LHC)

Hadron collider Higgs boson production processes



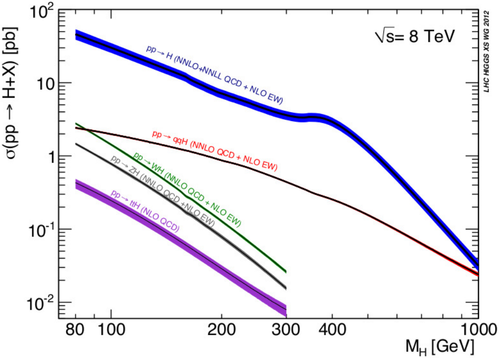
Gluon Fusion (GF) | Vector Boson Fusion (VBF) | Higgs Strahlung/V Assoc. Prod. | Heavy Quark Associated Prod.

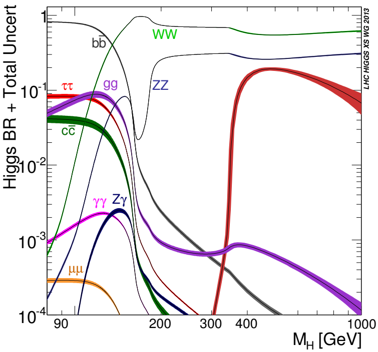
Higgs boson decay processes



adapted from Dittmaier, Schumacher arXiv:1211.4828

SM Higgs boson production and decay at the LHC





Discovery publications:

ATLAS, *Observation of a new particle in the search for the SM Higgs boson ...*, Phys. Lett. B **716** (2012) 1.

CMS, *Observation of a new boson at a mass of 125 GeV ...*, Phys. Lett. B **716** (2012) 30.

And many papers with updates and more detailed characterisation (couplings, spin/CP), e.g.:

ATLAS, *Measurements of Higgs boson production and couplings in diboson final states ...*, Phys. Lett. B **726** (2013) 88; ATLAS, *Updated coupling measurements of the Higgs boson ...*, ATLAS-CONF-2014-009; ATLAS, *Evidence for the spin-0 nature of the Higgs boson ...*, Phys. Lett. B **726** (2013) 120.

CMS, *Observation of a new boson with mass near 125 GeV ...*, JHEP **1306** (2013) 081; CMS, *Study of the mass and spin-parity of the Higgs boson candidate via its decays to Z boson pairs*, Phys. Rev. Lett. **110** (2013) 081803; CMS, *Measurement of the properties of a Higgs boson in the four-lepton final state*, Phys. Rev. D **89** (2014) 092007.

SM Higgs boson production and decay at the LHC

Experimental studies have been informed by numerous theoretical papers (too many to list), summarised in Higgs physics reviews, e.g.:

A. Djouadi, *The Anatomy of electro-weak symmetry breaking. I: The Higgs boson in the standard model*, Phys. Rept. **457** (2008) 1.

A. Djouadi, *The Anatomy of electro-weak symmetry breaking. II. The Higgs bosons in the minimal supersymmetric model*, Phys. Rept. **459** (2008) 1.

A. Djouadi, *Higgs Physics: Theory*, Pramana **79** (2012) 513.

D. Carmi, A. Falkowski, E. Kuflik, T. Volansky and J. Zupan, *Higgs After the Discovery: A Status Report*, JHEP **1210** (2012) 196.

L. Reina, *TASI 2011: lectures on Higgs-Boson Physics*, arXiv:1208.5504 [hep-ph].

S. Dittmaier and M. Schumacher, *The Higgs Boson in the Standard Model - From LEP to LHC: Expectations, Searches, and Discovery of a Candidate*, Prog. Part. Nucl. Phys. **70** (2013) 1.

Higgs Working Group Report of the Snowmass 2013 Community Planning Study, arXiv:1310.8361 [hep-ex].

J. Ellis, *Higgs Physics*, arXiv:1312.5672 [hep-ph].

H. E. Logan, *TASI 2013 lectures on Higgs physics within and beyond the Standard Model*, arXiv:1406.1786 [hep-ph].

J. Ellis, *LHCP 2014: Theory Summary and Prospects*, arXiv:1408.5866 [hep-ph].

and many others ...

and the LHC Higgs Cross Section Working Group reports (also other WGs, see above):

LHC Higgs Cross Section WG, *Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables*, CERN-2011-002.

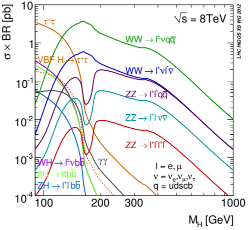
LHC Higgs Cross Section WG, *Handbook of LHC Higgs Cross Sections: 2. Differential Distributions*, CERN-2012-002.

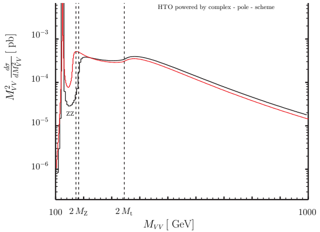
LHC Higgs Cross Section WG, *Handbook of LHC Higgs Cross Sections: 3. Higgs Properties*, CERN-2013-004.

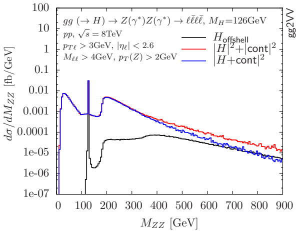
LHC Higgs Cross Section WG, *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, close to final.

bottom line: no compelling Standard Model deviations found so far, search continues in Run 2

$gg \to H \to ZZ, WW$: sizeable off-shell Higgs signal with large signal-background interference



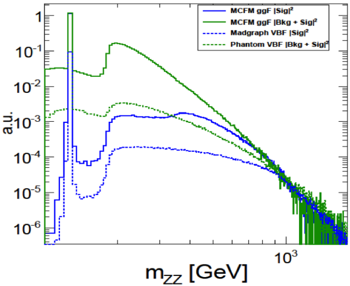


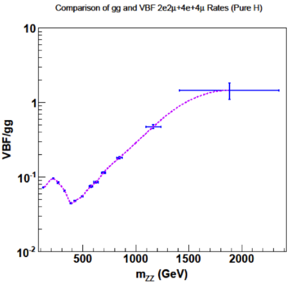


- $gg \to H \to VV \to 4\ell$ and $2\ell 2\nu$ signal-background interference very well studied at $\mathcal{O}(\alpha_s^2\alpha^4)$: Glover, van der Bij (1989); Kao, Dicus (1991); Binoth, Ciccolini, NK, Krämer (2006) (gg2WW); Campbell, Ellis, Williams (2011) (MCFM); NK (2012) (gg2VV); NK, Passarino (2012); Campanario, Li, Rauch, Spira (2012); Bonvini, Caola, Forte, Melnikov, Ridolfi (2013); Caola, Melnikov (2013); NK (2013) (gg2VV); Campbell, Ellis, Williams (2013) (MCFM); Campbell, Ellis, Williams (2014) (MCFM); Campbell, Ellis, Furlan, Röntsch (2014); related interference effects: Bredenstein, Denner, Dittmaier, Weber (2006) (PROPHECY4f); YR3: Denner, Dittmaier, Mück (2013) and Anderson, Bolognesi, Caola, Gao, Gritsan, Martin, Melnikov, Schulze, Tran, Whitbeck, Zhou (2013); Chen, Cheng, Gainer, Korytov, Matchev, Milenovic, Mitselmakher, Park, Rinkevicius, Snowball (2013); Chen, Vega-Morales (2013)
- tools for ggF: MCFM-6.8, gg2VV-3.1.7 ($gg \to VV$ parton-calculators and event generators), MadGraph5, Sherpa+OpenLoops (allows for merging of $gg \to VV + \{0, 1\}$ jets)
- loop technology closing in on calculation at $\mathcal{O}(\alpha_s^3\alpha^4)$ (see below) Aachen/FNAL/IPPP, Karlsruhe, Zurich
- gluon-fusion Higgs production and semileptonic decay: Dobrescu, Lykken (2010); Lykken, Martin, Winter (2012); Kao, Sayre (2012); ATLAS arXiv:1206.2443; ATLAS arXiv:1206.6074; CMS PAS HIG-13-008

Sizeable off-shell Higgs signal in vector boson fusion

- similar effect in VBF $H \to VV$ (NK, Passarino): $\mathcal{O}(10\%)$ of Higgs signal is off-shell
  note: no exp. sensitivity to off-shell $H \to VV$ tail in VH and $t\bar{t}H$ channels (see $\sigma_{\text{prod}}(M_H)$)
- total off-shell Higgs signal has $\sim 10\%$ VBF contribution





Covarelli, Anderson, Sarica

figures taken from Covarelli's talk at LHC HXSWG workshop (12 Jun 2014)

- tools for VBF: MadGraph5 Alwall et al., Phantom Ballestrero et al., VBFNLO Baglio et al., Sherpa+OpenLoops Cascioli et al.

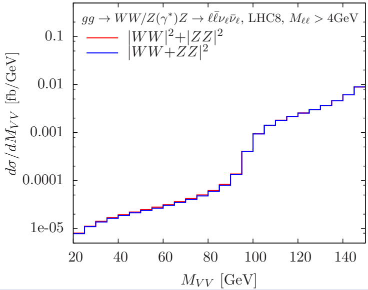
$gg \to H \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ interference (gg2VV)

Integrated cross sections (SM Higgs)

	$gg\,(\to H) \to VV \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$, σ [fb], pp, $\sqrt{s} = 8$ TeV, $M_H = 126$ GeV, min. cuts, $\mu_R = \mu_F = M_{\ell\bar{\nu}_\ell\bar{\ell}\nu_\ell}/2$			interference	
VV	H	cont	$\lvert H$+cont$\rvert^2$	R_1=(S+B+I)/(S+B)	R_2=(S+I)/S
WW	17.318(4)	16.925(4)	32.803(8)	0.9580(3)	0.9169(6)
ZZ	0.8822(2)	2.1553(6)	2.872(1)	0.9455(4)	0.813(2)
WW/ZZ	17.402(3)	19.084(4)	34.884(7)	0.9561(3)	0.9079(5)
R_3	0.9562(3)	1.0002(3)	0.9778(3)	$\sigma(\lvert WW + ZZ\rvert^2)/\sigma(\lvert WW\rvert^2 + \lvert ZZ\rvert^2)$	
R_4	0.9540(3)	1.0002(4)	0.9759(4)	$(\sigma(\lvert WW\rvert^2) + I_{WW/ZZ})/\sigma(\lvert WW\rvert^2)$	
R_6	0.05094(2)	0.12735(5)	0.08756(4)	$\sigma(\lvert ZZ\rvert^2)/\sigma(\lvert WW\rvert^2)$	

minimal cuts: WW/ZZ interference: Higgs signal: ≈5%, gg continuum: negligible NK arXiv:1310.7011

Differential cross sections



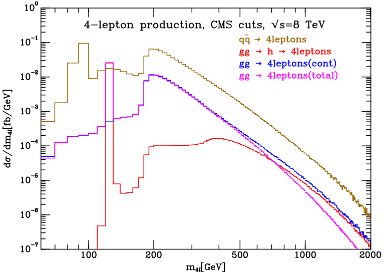
$gg \to WW/ZZ$ continuum: M_{VV} distribution

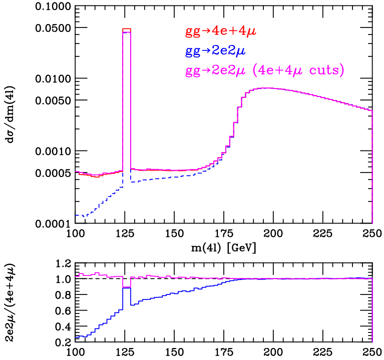
$M_{VV} > 95$ GeV: WW/ZZ interference negligible

$M_{VV} < 95$ GeV: WW/ZZ interference of $\approx 5\%$

see also: $H \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ interference at LO & NLO Mück, Bredenstein, Denner, Dittmaier, Weber YR3 arXiv:1307.1347, Sec. 2.2

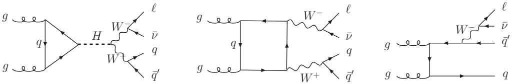
$gg \to H \to ZZ \to 4\ell$ interference (MCFM)





Campbell, R.K. Ellis, Williams   figures taken from arXiv:1408.1723

Interference for semileptonic H decay modes in ggF



$$\mathcal{M} = \mathcal{M}_{signal}\text{ (LO) } + \mathcal{M}_{background} = \mathcal{M}_{signal} + \mathcal{M}_{loop} + \mathcal{M}_{tree}$$

Notation for amplitude contributions to cross sections:

$$\begin{aligned} S &\sim |\mathcal{M}_{signal}|^2 \\ I_{tree} &\sim 2\,\mathrm{Re}(\mathcal{M}^*_{signal}\,\mathcal{M}_{tree}) \\ I_{loop} &\sim 2\,\mathrm{Re}(\mathcal{M}^*_{signal}\,\mathcal{M}_{loop}) \\ I_{full} &\sim 2\,\mathrm{Re}(\mathcal{M}^*_{signal}\,\mathcal{M}_{background}) \end{aligned}$$

$\mathcal{M}_{loop}$ contains all quark loop graphs. (EW corrections to I_{tree} not included.)

relative measure for interf. with bkg. i: $$R_i = \frac{\sigma(|\mathcal{M}_{signal}|^2 + 2\,\mathrm{Re}(\mathcal{M}^*_{signal}\mathcal{M}_i))}{\sigma(|\mathcal{M}_{signal}|^2)}$$

Interference for semileptonic H decay modes in ggF

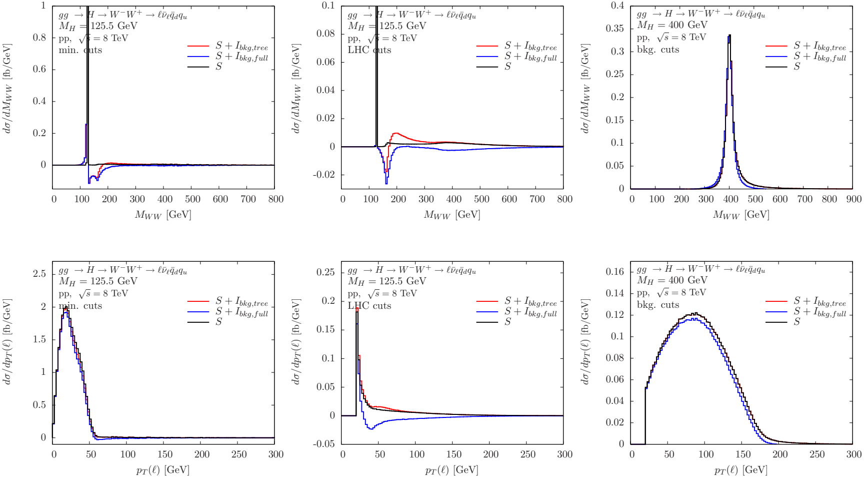
$gg \to H \to ZZ \to \ell\bar{\ell}q_u\bar{q}_u$ σ [fb], pp, $\sqrt{s} = 8$ TeV		interference			ratio		
cuts	S	I_{tree}	I_{loop}	I_{full}	R_{tree}	R_{loop}	R_{full}
min.	1.96(1)	–0.190(4)	–0.343(3)	–0.541(5)	0.903(7)	0.825(7)	0.724(7)
LHC	0.1166(6)	0.017(2)	–0.194(2)	–0.176(6)	1.15(2)	–0.67(2)	–0.51(5)
bkg.	1.342(7)	–0.0012(2)	–0.0882(9)	–0.0892(9)	0.999(7)	0.934(7)	0.934(7)

$gg \to H \to ZZ \to \ell\bar{\ell}q_d\bar{q}_d$ σ [fb], pp, $\sqrt{s} = 8$ TeV		interference			ratio		
cuts	S	I_{tree}	I_{loop}	I_{full}	R_{tree}	R_{loop}	R_{full}
min.	2.51(2)	–0.248(3)	–0.439(6)	–0.680(7)	0.901(7)	0.825(7)	0.729(7)
LHC	0.1497(8)	0.0223(6)	–0.245(5)	–0.227(3)	1.149(9)	–0.64(3)	–0.52(2)
bkg.	1.720(9)	–0.00130(5)	–0.113(1)	–0.114(1)	0.999(7)	0.934(7)	0.934(7)

higher-order background contributions can induce leading interference effects

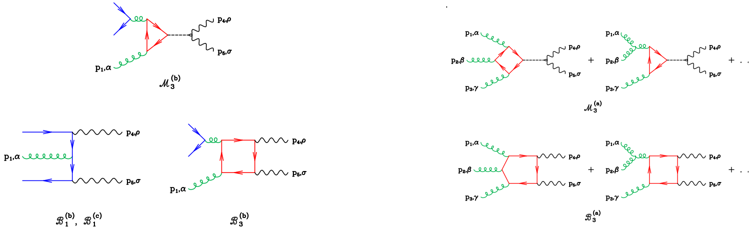
NK, C. O'Brien, E. Vryonidou arXiv:1506.01694 (gg2VV and MadGraph5_aMC@NLO)

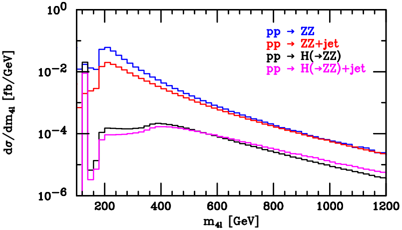
Interference for semileptonic H decay modes in ggF

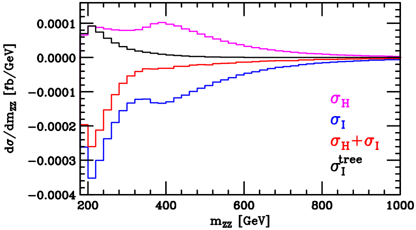


NK, C. O'Brien, E. Vryonidou arXiv:1506.01694

Interference for $pp \to H \to ZZ$ + jet







off-shell Higgs cross sections for ZZ and ZZ+jet comparable ($p_{Tj} > 30$ GeV)

Campbell, R.K. Ellis, Furlan, Röntsch   figures taken from arXiv:1409.1897

Z bosons treated in zero-width approximation (validated for ZZ final state: excellent for $m_{4l} > 300$ GeV)

Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

Signal: $gg \to H$ cross section at NLO QCD with finite t and b mass effects (important for off-shell Higgs with $M_{VV} \gtrsim 2M_t$: 5–10% correction) (scale uncertainty: 10–15%) Djouadi, Spira, Zerwas, Graudenz (1991-1995); N^{3}LO in soft expansion with $M_t \to \infty$ (scale uncertainty $\approx 3\%$) C. Anastasiou, C. Duhr, F. Dulat, F. Herzog, B. Mistlberger arXiv:1503.06056; NLO EW corrections important for off-shell Higgs (8% at $M_{VV} \sim 500$ GeV) A. Bredenstein, A. Denner, S. Dittmaier, M. Weber arXiv:hep-ph/0604011 (also arXiv:1111.6395)

Background: $pp \to ZZ$ and $pp \to WW$ at NNLO QCD with massless quarks (scale uncertainty $\approx 3\%$), F. Cascioli, T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhofer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi, E. Weihs arXiv:1405.2219 and T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhofer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi arXiv:1408.5243

$gg \to VV$ enters $pp \to VV$ at $\mathcal{O}(\alpha_s^2\alpha^2)$ (NNLO QCD correction to $pp \to VV$) with $\sim$ 20–25% (LO!) scale uncertainty; $\mathcal{O}(\alpha_s^3\alpha^2)$: unknown $gg \to VV$ NLO QCD K-factor, but expected to be similar to signal (~ 1.6); confirmed by $gg \to ZZ$ NLO QCD calculation in massless quark approximation (see next page)

11–17% (9–12%) NNLO QCD correction to $pp \to ZZ$ (WW) for $\sqrt{s} = 7$–14 TeV

$gg \to VV$ contributes to full NNLO correction to $pp \to ZZ$ (WW) with 60% (35%)

$\to$ NLO QCD correction to $gg \to VV$ is of similar size or larger than residual scale uncertainty of $pp \to VV$ at NNLO QCD $\Rightarrow$ calculation is important and by a similar argument the calculation of the NLO QCD correction to signal-background interference

Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

Work towards $gg\ (\to H) \to VV$ signal-background interference and $gg \to VV$ continuum background beyond leading order, i.e. beyond $\mathcal{O}(\alpha_s^2)$:

NLO and NNLO calculation for $gg\ (\to H) \to WW \to \ell\nu\ell\nu$ interference with $M_H = 600$ GeV in soft-gluon approximation (very good accuracy for inclusive signal cross section)
M. Bonvini, F. Caola, S. Forte, K. Melnikov, G. Ridolfi arXiv:1304.3053
$\to$ interference K-factors are generally very similar to signal K-factors (also for kinematic distributions)

Soft gluon resummation to all orders for $gg\ (\to H) \to ZZ \to \ell\ell\ell'\ell'$ interference, 100 GeV $< M_{ZZ} < 1000$ GeV, effects signal like C. Li, H. Li, D. Shao, J. Wang arXiv:1504.02388

Technical bottleneck for unapproximated $gg \to VV$ calc. at NLO: two-loop virtual corrections

Two-loop $gg \to VV \to 4$ leptons amplitudes with massless quarks calculated by two groups:
F. Caola, J. Henn, K. Melnikov, A. Smirnov, V. Smirnov arXiv:1503.08759
A. v. Manteuffel, L. Tancredi arXiv:1503.08835

Calculation of NLO $gg \to ZZ$ cross section in model where Z bosons only couple to t quarks in s/M_t^2 expansion (LO) yields K-factor of 1.5–2 for 180 GeV $< M_{ZZ} < 340$ GeV
(LO QCD comparison with exact M_t: $M_t \to \infty$ poor for $M_{ZZ} \gtrsim 300$ GeV)
K. Melnikov, M. Dowling arXiv:1503.01274

Calculation of NLO $gg \to ZZ$ (WW) cross section in massless quark approximation yields K-factor of 1.5–2 (1.2–1.8, jet veto!) F. Caola, K. Melnikov, R. Röntsch, L. Tancredi arXiv:1509.06734 (arXiv:1511.08617), $gg \to WW$: no t–b loop graphs $\to$ $\mathcal{O}(10\%)$ missing

Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

2-loop calculation with full top mass dependence beyond current capabilities for continuum background amplitude

Approximate using method of *expansion by regions* V.A. Smirnov et al.:
Large Mass Expansion (LME): expand in s/m_t^2,
formally valid for $s < m_t^2$, but extrapolation to $s \gg m_t^2$ feasible with reasonable accuracy (1605.01380: $10\% - 20\%$)

$gg \to ZZ$: first-order expansion by Dowling, Melnikov (1503.01274), suppressed Vec. $t\bar{t}Z$ coupling is missing

$gg \to ZZ$: recent, complementary extensions to high orders (~ 6) in s/m_t^2:

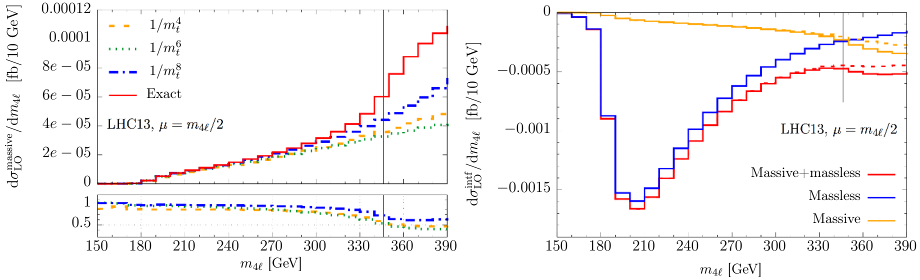
J. Campbell, K. Ellis, M. Czakon, S. Kirchner arXiv:1605.01380
on-shell Z's: $M_{ZZ} > 2M_Z$, extrapolation to $s \gg m_t^2$

F. Caola, M. Dowling, K. Melnikov, R. Röntsch, L. Tancredi arXiv:1605.04610
off-shell Z's including leptonic decays for $s \lesssim (2m_t)^2$

Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

F. Caola, M. Dowling, K. Melnikov, R. Röntsch, L. Tancredi

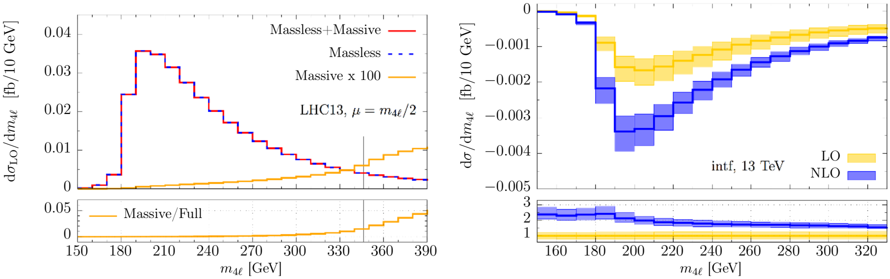
LO 4-lepton invariant mass distribution (massive: LME vs. exact),
left: background only, right: interference



Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

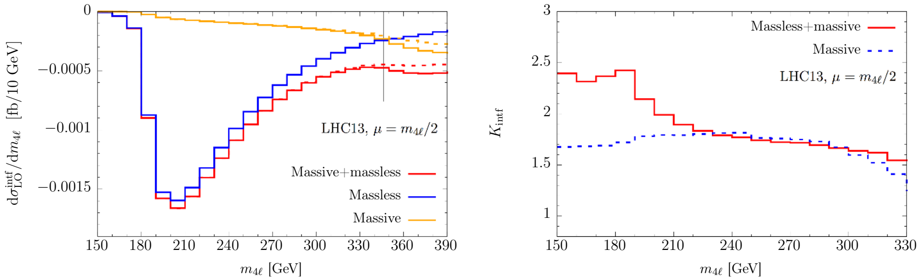
F. Caola, M. Dowling, K. Melnikov, R. Röntsch, L. Tancredi

4-lepton invariant mass distributions, left: background only (LO),
right: interference with factor-2 scale variation (lower panel: K-factor)



Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

F. Caola, M. Dowling, K. Melnikov, R. Röntsch, L. Tancredi



$m_{4\ell} \sim 2m_t$: $K_{\text{signal}} \approx K_{\text{bkg}} \approx K_{\text{intf}}$

$m_{4\ell} \sim 2M_Z$: K_{intf} different from K_{signal} and K_{bkg}

$K_{\text{intf}} \approx \sqrt{K_{\text{signal}} K_{\text{bkg}}}$ for full considered $m_{4\ell}$ range

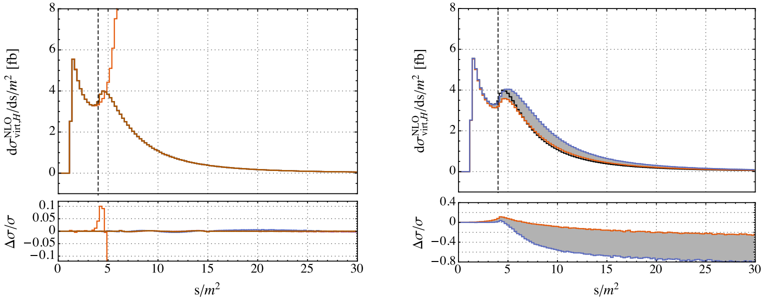
Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

J. Campbell, K. Ellis, M. Czakon, S. Kirchner

Improving naive LME with

1. Conformal Mapping, Padé approximants (superior, selected)
2. Rescaling with exact LO result

Test with H signal: Comparison (improved) LME vs. exact for virtual NLO corrections: left: 1., right: 2.

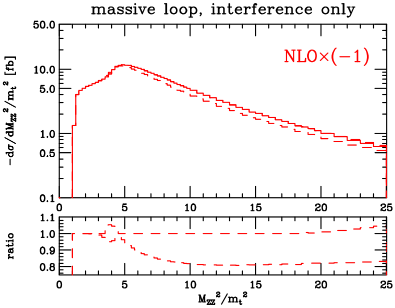


similar behaviour found when comparing for LO $gg \to ZZ$ continuum

Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

J. Campbell, K. Ellis, M. Czakon, S. Kirchner

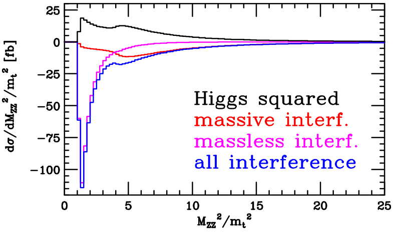
Uncertainty on NLO interference due to improved LME ($\lesssim 20\%$ on approximated part):

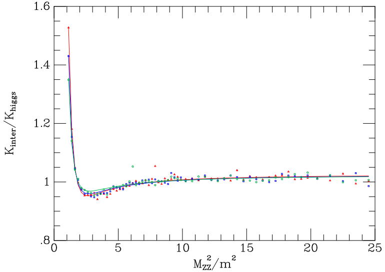


Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

J. Campbell, K. Ellis, M. Czakon, S. Kirchner

Full prediction and ratio of K-factors for interference and signal:





Higgs width measurement in a nutshell

- Total Higgs width Γ_H is not a fundamental parameter of the theory, but of great phenomenological interest (Higgs mechanism $\rightarrow$ overall coupling strength)
- Direct Higgs width measurement via resonance shape is limited at LHC by experimental mass resolution of $\mathcal{O}(1)$ GeV (CMS: $\Gamma_H < 2.4$ GeV, but note that $\Gamma_{H,SM} \approx 4$ MeV)
- All resonant Higgs cross sections depend on Γ_H, therefore Γ_H and couplings cannot be determined at the LHC (on-peak) without theoretical assumptions M. Duhrssen et al. (2004), LHC Higgs Cross Section WG (2012)
- For broad class of models, assuming upper limit for HWW or HZZ coupling (e.g. SM) $\rightarrow$ upper bound for Γ_H $(\Gamma_H = \mathcal{O}(\Gamma_{H,SM}))$ M. Peskin (2012); B. Dobrescu, J. Lykken (2013)
- Assuming no BSM Higgs decays, and Higgs coupling parameterisations, can fit Higgs width to data and agreement with SM Higgs width is found V. Barger, M. Ishida, W. Keung (2012); K. Cheung, J. Lee, P. Tseng (2013); J. Ellis, T. You (2013); A. Djouadi, G. Moreau (2013); P. Bechtle, S. Heinemeyer, O. Stal, T. Stefaniak, G. Weiglein (2014)
- $e^+e^- \rightarrow Z(H \rightarrow \text{all})$: construct recoil mass and measure HZZ coupling $\rightarrow \Gamma_H$ can be determined indirectly, ILC: 6%–11% accuracy M. Peskin (2013), T. Han et al. (2013)
- Direct threshold scan at muon collider: Γ_H accuracy 4%–9% T. Han, Z. Liu (2013)
- Higgs width determination could provide first evidence for BSM Higgs interactions

Off-shell Higgs signal and Higgs width determination

indirect Higgs width determination via on- and off-peak Higgs cross section

F. Caola, K. Melnikov (2013) arXiv:1307.4935

$$|\mathcal{M}_{i\to H\to f}|^2 = \frac{|\mathcal{M}_i|^2\,|\mathcal{M}_f|^2}{|p_H^2 - M_H^2 + iM_H\Gamma_H|^2}$$

resonance contribution to signal cross section ("on-peak"): $\sigma_{i\to H\to f} \overset{\text{NWA}}{\propto} \frac{g_i^2 g_f^2}{\Gamma_H}$

NWA scaling degeneracy: σ unchanged if $g_i \to \xi\, g_i,\;\; g_f \to \xi\, g_f,\;\; \Gamma_H \to \xi^4\,\Gamma_H$

cf. L. Dixon, Y. Li arXiv:1305.3854 (see below)

$$\sqrt{p_H^2} - M_H \gg \mathcal{O}(\Gamma_H) \;\to\; p_H^2 - M_H^2 \gg M_H\Gamma_H \;\to\; |\mathcal{M}_{i\to H\to f}|^2 \approx \frac{|\mathcal{M}_i|^2\,|\mathcal{M}_f|^2}{|p_H^2 - M_H^2|^2}$$

off-resonance contribution ("off-peak"): $\sigma_{i\to H\to f}\left(\sqrt{p_H^2} - M_H \gg \mathcal{O}(\Gamma_H)\right) \propto g_i^2 g_f^2$

sizeable off-resonance contribution to signal cross section is independent of Higgs width, and therefore "breaks" NWA scaling degeneracy: $\sigma_{\text{off-peak}}/\sigma_{\text{on-peak}} \propto \Gamma_H$

competitive constraints on Higgs width without assumptions(?) feasible with LHC data

large interference with cont. background (necessary to prevent unitarity violation) weakens bounds

MCFM analysis

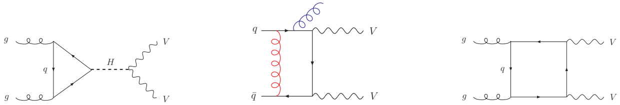
J. Campbell, K. Ellis, C. Williams (2013) (update of Caola-Melnikov analysis)

CMS Higgs selection cuts are applied:

$p_{T\ell 1} > 20$ GeV, $p_{T\ell 2} > 10$ GeV, $p_{Te} > 7$ GeV, $p_{T\mu} > 5$ GeV, $|\eta_\mu| < 2.4$, $|\eta_e| < 2.5$, $M_{\ell\bar{\ell}} > 4$ GeV, $M_{4\ell} > 100$ GeV, 40 GeV $< M_{\ell\bar{\ell},\text{closest}} < 120$ GeV, 12 GeV $< M_{\ell\bar{\ell},\text{other}} < 120$ GeV (relative to M_Z)

Best prediction cross sections for $pp \to H \to ZZ \to e^-e^+\mu^-\mu^+$ in fb, obtained using the running scale $m_{4\ell}/2$:

Energy	PDF	σ^H_{peak}	$m_{4\ell} > 130$ GeV σ^H_{off}	$m_{4\ell} > 130$ GeV σ^I_{off}	$m_{4\ell} > 300$ GeV σ^H_{off}	$m_{4\ell} > 300$ GeV σ^I_{off}
7 TeV	MSTW	0.203	0.025	-0.053	0.017	-0.025
	CTEQ	0.192	0.021	-0.047	0.015	-0.021
8 TeV	MSTW	0.255	0.034	-0.073	0.025	-0.036
	CTEQ	0.243	0.031	-0.065	0.022	-0.031
13 TeV	MSTW	0.554	0.108	-0.215	0.085	-0.122
	CTEQ	0.530	0.100	-0.199	0.077	-0.111



MCFM analysis

For $\sigma_{off} = \sigma_{off}^H + \sigma_{off}^I$ with $\sqrt{s} = 8$ TeV and MSTW PDF set: $\xi^4 = \Gamma_H/\Gamma_H^{SM}$

$$\sigma_{off}(m_{4\ell} > 130 \text{ GeV}) = 0.034 \underbrace{\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right)}_{\text{Higgs signal}} -0.073 \underbrace{\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}}_{\text{interference}}$$

$$\sigma_{off}(m_{4\ell} > 300 \text{ GeV}) = 0.025 \left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 0.036 \sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

Normalising to the number of events observed at the peak one can estimate number of Higgs-related off-peak events (properly combining 7 and 8 TeV data used in CMS $H \to ZZ \to 4\ell$ analysis):

$$N_{off}^{4\ell}(m_{4\ell} > 130 \text{ GeV}) = 2.78 \left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 5.95 \sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

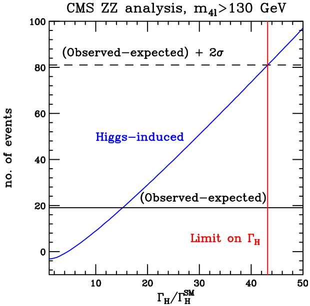
$$N_{off}^{4\ell}(m_{4\ell} > 300 \text{ GeV}) = 2.02 \left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 2.91 \sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

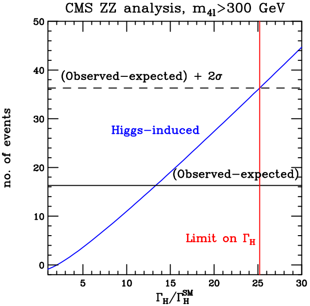
Second term accounts for interference between $gg \to H \to ZZ \to 4\ell$ (Higgs signal amplitude) and $gg \to ZZ \to 4\ell$ (continuum background amplitude)

MCFM analysis

Higgs width bounds from cut-based analysis

Using event number observed in off-peak region (451) and number expected from continuum background only (431 ± 31):





$\Gamma_H < 43.2\,\Gamma_H^{SM}$ (95% CL), $\quad (m_{4\ell} > 130 \text{ GeV analysis})$

$\Gamma_H < 25.2\,\Gamma_H^{SM}$ (95% CL), $\quad (m_{4\ell} > 300 \text{ GeV analysis})$

Method can be applied to $H \to WW$ channel (M_T), comparable bounds appear feasible MCFM (2013)

MCFM analysis

Higgs width bounds from matrix element method ($H \to ZZ$)

Matrix element method: optimize discrimination using fully differential information

Associate probabilistic weight with each event:

$$P(\phi) = \frac{1}{\sigma} \sum_{i,j} \int dx_1 dx_2 \, \delta(x_1 x_2 s - Q^2) f_i(x_1) f_j(x_2) \hat{\sigma}_{ij}(x_1, x_2, \phi)$$

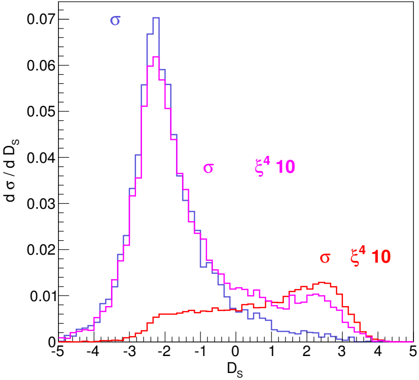
$P_{q\bar{q}}$: $q\bar{q}$ induced continuum background

P_{gg} : gg induced contributions
(incl. Higgs signal, cont. bkg. & interf.)

P_H : gg induced Higgs amplitude squared

Discriminant:

$$D_S = \log\left(\frac{P_H}{P_{gg} + P_{q\bar{q}}}\right)$$



$$\Gamma_H < \left(15.7^{-2.9}_{+3.9}\right) \Gamma_H^{SM} \text{ (95\% CL)}, \quad (D_S > 1)$$

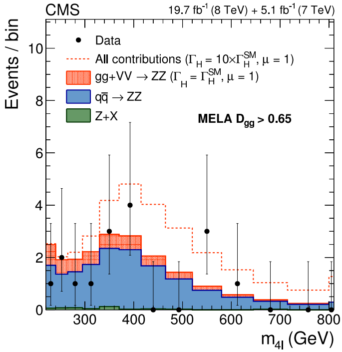
bound $1.6\times$ better than for $m_{4\ell} > 300$ GeV

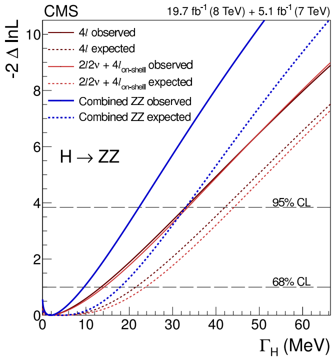
CMS analysis

arXiv:1405.3455 (May 2014)

improvements:

- include $2\ell 2\nu$ final states
- include VBF channel (contributes $\sim 7\%$ on peak, and $\mathcal{O}(10\%)$ above $2M_Z$)
- include known QCD and EW corrections F. Caola, T. Kasprzik, G. Passarino, M. Zaro et al.
- slightly different kinematic discriminant ($P_H \to P_{gg}$), backgrounds fully considered





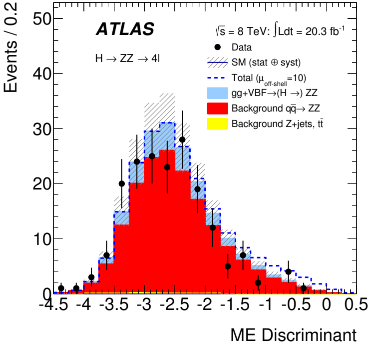
$$\Gamma_H < 5.4\,\Gamma_H^{SM}\ \text{(95\% CL)}$$

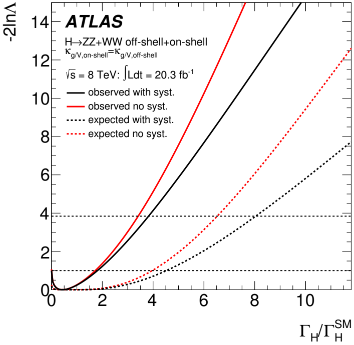
ATLAS analysis

arXiv:1503.01060 (July 2014, March 2015)

improvements:

- similar to CMS, thorough consideration of systematic uncertainties
- provide results as function of the unknown $gg \to ZZ$ background K-factor, variation: $[0.5, 2] \times$ signal K-factor
- off-shell signal strength 95%-CL upper limit $[5.1, 8.6]$ ($[6.7, 11]$ expected)



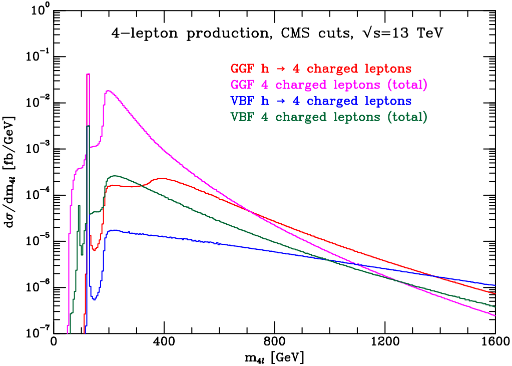


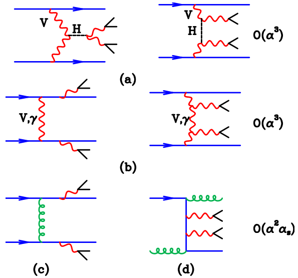
$$\Gamma_H < [4.5, 7.5]\,\Gamma_H^{SM} \text{ (95\% CL)}$$

Higgs (width) constraints from vector boson fusion

J.M. Campbell, R.K. Ellis, arXiv:1502.02990

(see also C. Englert, M. Spannowksy arXiv:1405.0285, C. Englert, M. McCullough, M. Spannowksy arXiv:1504.02458)





most sensitive off-sh. channel: $W^\pm W^\pm$ due to lower bkg. (t-channel Higgs!)

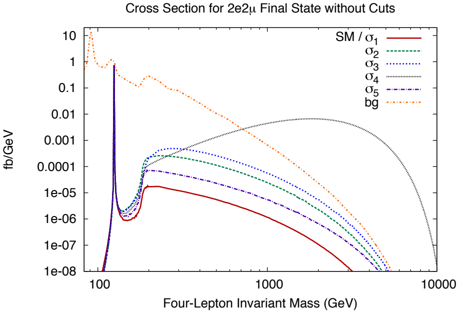
$\Gamma_H < 61\ \Gamma_H^{SM}$ (LHC Run 1)

$\Gamma_H < 4.4\ \Gamma_H^{SM}$ (LHC 100 fb^{-1} data)

$\Gamma_H < 3.2\ \Gamma_H^{SM}$ (LHC 300 fb^{-1} data)

BSM searches and model builder's considerations

Constraining higher dimensional operators with the off-shell Higgs (see below)
Disentangling New Physics with the off-shell Higgs boson
EFT studies including the off-shell Higgs boson
Limitations of model independence



$$\mathcal{O}_1 = -\frac{M_Z^2}{v} H Z_\mu Z^\mu \text{ (SM)},\ \mathcal{O}_2 = -\frac{1}{2v} H Z_{\mu\nu} Z^{\mu\nu},\ \mathcal{O}_3 = -\frac{1}{2v} H Z_{\mu\nu} \widetilde{Z}^{\mu\nu},\ \mathcal{O}_4 = \frac{M_Z^2}{M_H^2 v} Z_\mu Z^\mu \partial^2 H,$$

$$\mathcal{O}_5 = \frac{2}{v} H Z_\mu \partial^2 Z^\mu$$

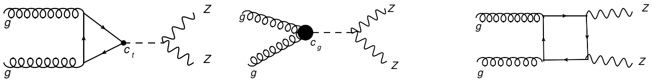
J. Gainer, J. Lykken, K. Matchev, S. Mrenna, M. Park arXiv:1403.4951

Also: modification of lepton angular distributions $\longrightarrow$ good control with 300 fb^{-1} I. Anderson et al. arXiv:1309.4819

EFT analysis of on- and off-shell $H \to ZZ \to 4\ell$ data

A. Azatov, C. Grojean, A. Paul, E. Salvioni (2014)

(see also G. Cacciapaglia, A. Deandrea, G. Drieu La Rochelle, J. Flament (PRL 2014))

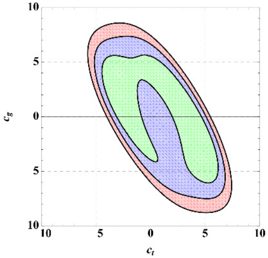


$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t}th + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu}G^{\mu\nu}$$

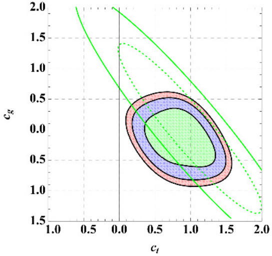
$$\mathcal{M}_{gg\to ZZ} = \mathcal{M}_h + \mathcal{M}_{bkg} = c_t \mathcal{M}_{c_t} + c_g \mathcal{M}_{c_g} + \mathcal{M}_{bkg}$$

$\sigma \sim |c_t + c_g|^2$: on-shell degeneracy $c_t + c_g = \text{const}$ is broken by far-off-shell data

Constraints in (c_t, c_g) plane $(68\%, 95\%$ and 99% probability contours): (not MELA improved!)

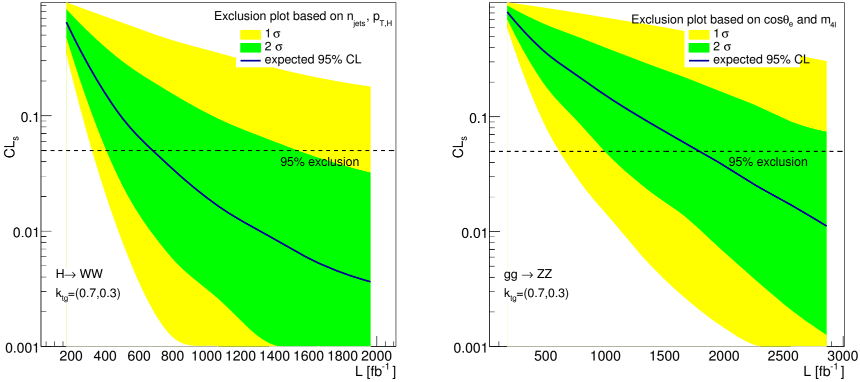


LHC 8 TeV CMS data



LHC 14 TeV $3\,\text{ab}^{-1}$ data

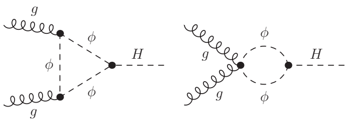
Effective ggH coupling: boosted v. off-shell Higgs sensitivity

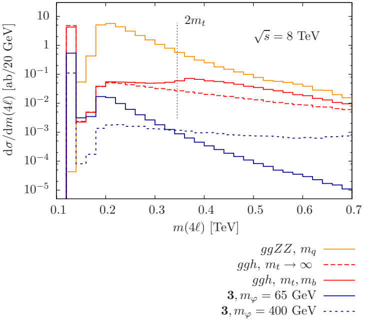


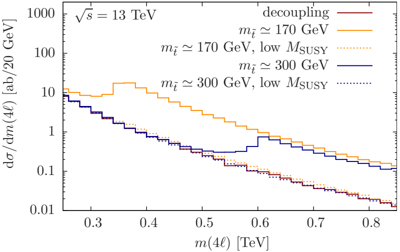
left: boosted analysis, right: off-shell analysis (not MELA improved)

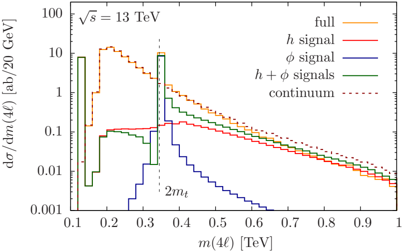
M. Buschmann, D. Goncalves, S. Kuttimalai, M. Schoenherr, F. Krauss, T. Plehn (2014) (1410.5806)

BSM benchmark scenario studies





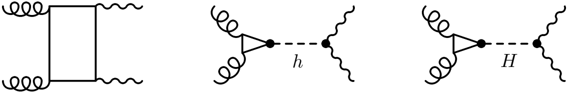




C. Englert, M. Spannowsky arXiv:1405.0285,1410.5440

Loophole: additional light scalar in the s-channel

[H.E. Logan, 1412.7577]



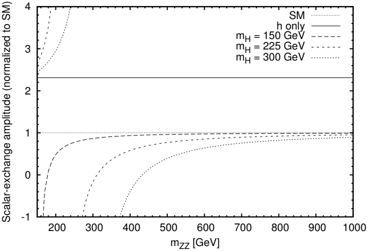
SM: h cancels growth $\propto E/v$ of $t\bar{t} \to ZZ$ amplitude.

Modified h couplings: cancellation imperfect; growth of amplitude with E provides LHC sensitivity at high m_{ZZ}!

Extended Higgs sector: Require $\kappa_t^h \kappa_Z^h + \kappa_t^H \kappa_Z^H = 1$ for unitarity of $t\bar{t} \to ZZ$ (automatic in renormalizable models): $\kappa_t^h \kappa_Z^h = 1 + \Delta > 1, \quad \kappa_t^H \kappa_Z^H = -\Delta$

Amplitude relative to SM:

$$\frac{\mathcal{M}_h + \mathcal{M}_H}{\mathcal{M}_{h_{\rm SM}}} = (1+\Delta) - \Delta \frac{p^2 - m_h^2}{p^2 - m_H^2}$$
$$\simeq 1 - \Delta \frac{(m_H^2 - m_h^2)}{p^2}$$
$$\to 1 \text{ for } p^2 \gg m_{h,H}^2$$

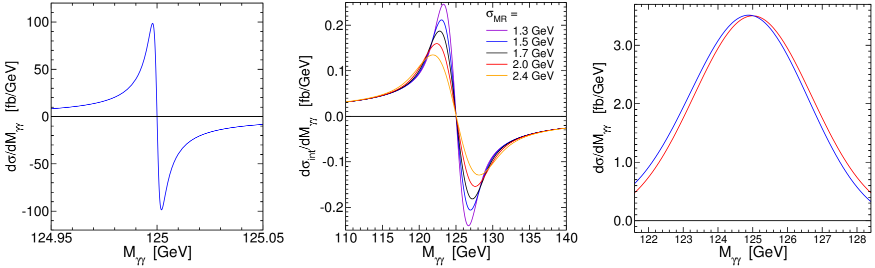


Presence of H at low mass (well below 350 GeV) causes $gg \to ZZ$ cross section to be SM-like at high m_{ZZ}, even if $\kappa_t^h \kappa_Z^h$ is strongly non-SM-like.

Higgs width via interferometry in $gg \to H \to \gamma\gamma$

S. Martin arXiv:1208.1533 (LO analysis of Higgs mass peak shift)

Higgs signal continuum background interference induces sizeable peak shift in $gg \to H \to \gamma\gamma$ (but negligible in $gg \to H \to ZZ^*$)



left fig.: interference contribution (real term) before detector resolution effects

center fig.: interference contribution (real term) for different mass resolutions (Gaussian, σ_{MR})

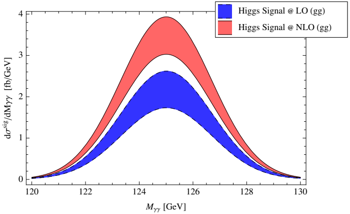
right fig.: peak shift of invariant mass distribution ($\sigma_{\text{MR}} = 1.7$ GeV): $\Delta M_{\gamma\gamma} = -120$ MeV at LO

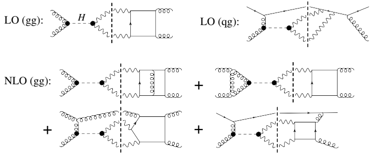
$(H \to \gamma\gamma)$+jet at LO: negligible mass peak shift (< 20 MeV for $p_{Tj} > 25$ GeV)

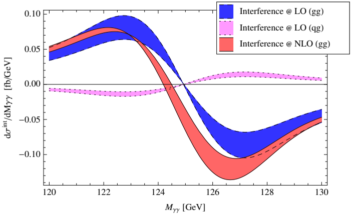
Daniel de Florian, et al. arXiv:1303.1397; S. Martin arXiv:1303.3342

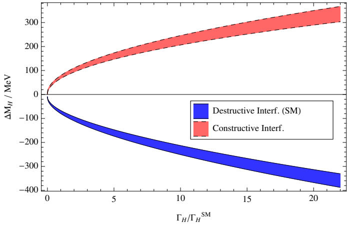
Higgs width via interferometry in $gg \to H \to \gamma\gamma$

L. Dixon, Y. Li arXiv:1305.3854 (NLO analysis and Higgs width constraint)









SM mass shift: $\Delta M_{\gamma\gamma} = -70$ MeV at NLO

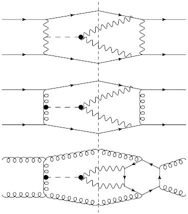
Vary Higgs width and couplings (maintaining on-peak SM signal strenghts):

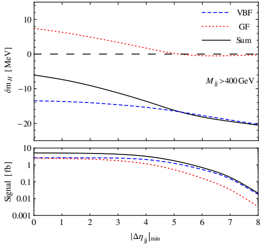
$$\Gamma_H < 15\,\Gamma_H^{SM}\ (14\text{ TeV},\ 3\text{ ab}^{-1},\ 95\%\text{ CL})$$

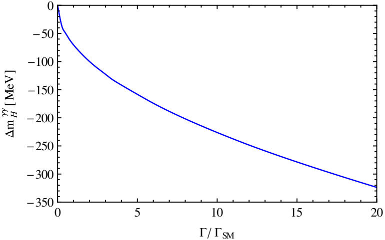
Higgs width via interferometry in $gg \to H \to \gamma\gamma$ with VBF $H \to \gamma\gamma$ mass peak as reference

Calculation of $pp \to H\ (\to \gamma\gamma) + 2$ jets signal (VBF and GF) and interference with background (LO)

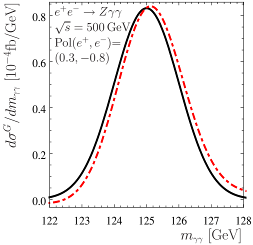
F. Coradeschi, D. de Florian, L. Dixon, N. Fidanza, S. Hoeche, H. Ita, Y. Li, J. Mazzitelli arXiv:1504.05215







$\Delta m_H^{\gamma\gamma} \equiv \delta m^{\gamma\gamma}_{H+X,\text{NLO,incl}} - \delta m^{\gamma\gamma}_{H+2j,\text{LO,VBF cuts}}$

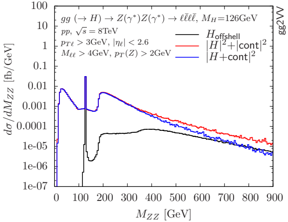


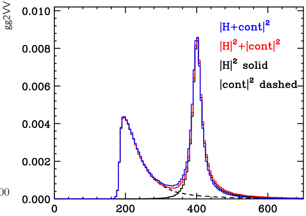
LC: $H \to \gamma\gamma$ mass peak shift S. Liebler arXiv:1503.07830

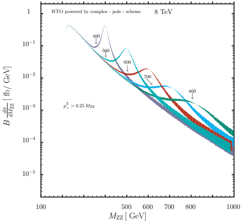
Heavy Higgs - light Higgs - continuum VV interference

consider a heavy Higgs h_2 (signal) in addition to a light Higgs h_1 at 125 GeV (background)

Two-Higgs model: SM & real EW singlet scalar, as defined in YR3 arXiv:1307.1347, Sec. 13.3





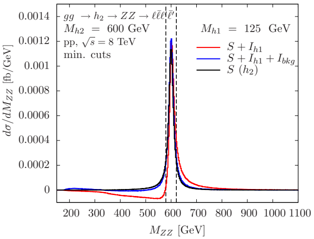


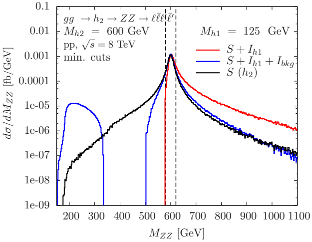
right fig.: G. Passarino (arXiv:1206.3824)

What is the impact of interference with the offshell tail of the 125 GeV Higgs for a heavy Higgs of 300, 600 or 900 GeV?

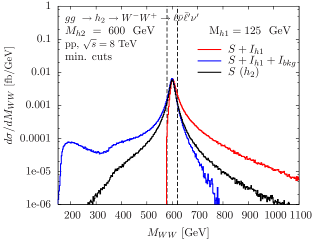
$$S \sim |\mathcal{M}_{h2}|^2$$
$$I_{h1} \sim 2\,\mathrm{Re}(\mathcal{M}_{h2}^*\,\mathcal{M}_{h1})$$
$$I_{bkg} \sim 2\,\mathrm{Re}(\mathcal{M}_{h2}^*\,\mathcal{M}_{bkg})$$
$$I_{full} \sim 2\,\mathrm{Re}(\mathcal{M}_{h2}^*\,(\mathcal{M}_{h1} + \mathcal{M}_{bkg}))$$

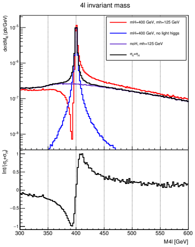
Heavy Higgs - light Higgs - continuum VV interference

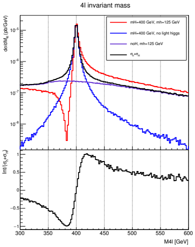




NK, C. O'Brien arXiv:1502.04113







NK, C. O'Brien

E. Maina arXiv:1501.02139

see also C. Englert, I. Low, M. Spannowsky arXiv:1502.04678, C. Englert, Y. Soreq, M. Spannowsky arXiv:1410.5440,

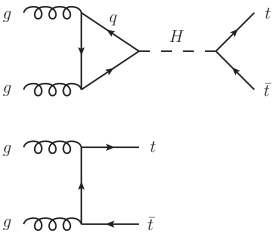
S. Dawson, I.M. Lewis arXiv:1605.04944, S.P. Martin arXiv:1606.03026

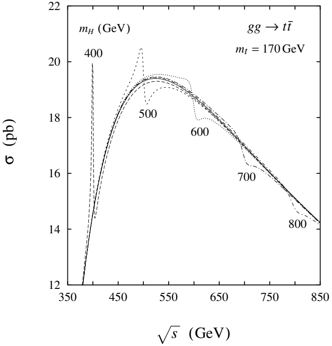
Aside: Heavy Higgs - continuum $t\bar{t}$ interference

peak-dip structure of Higgs invariant mass distribution

due to interference between $gg \to H \to t\bar{t}$ (signal) and $gg \to t\bar{t}$ (background)

interference pattern is similar to VV: negative interference above Higgs peak





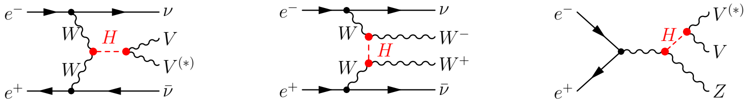
here: H is the heavy CP-even Higgs boson in the MSSM (CP-odd case is similar)

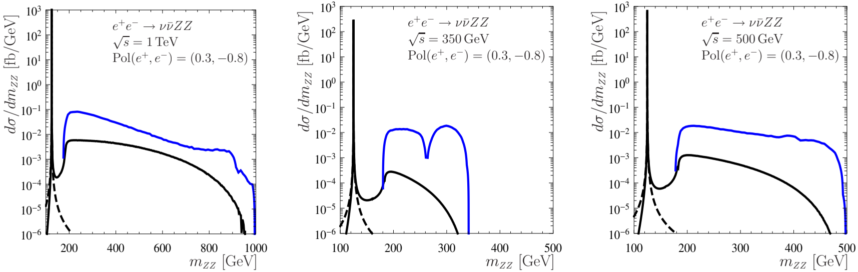
assumptions: $\tan\beta \approx 1$, $t\bar{t}H$ coupling $\sim$ SM, $H \to t\bar{t}$ decay is dominant (top decay is not included)

Dicus, Stange, Willenbrock hep-ph/9404359, Bernreuther, Galler, Mellein, Si, Uwer arXiv:1511.05584, Djouadi, Ellis, Quevillon arXiv:1605.00542, Hespel, Maltoni, Vryonidou arXiv:1606.04149

High-mass $H \to VV$ signal at a linear collider

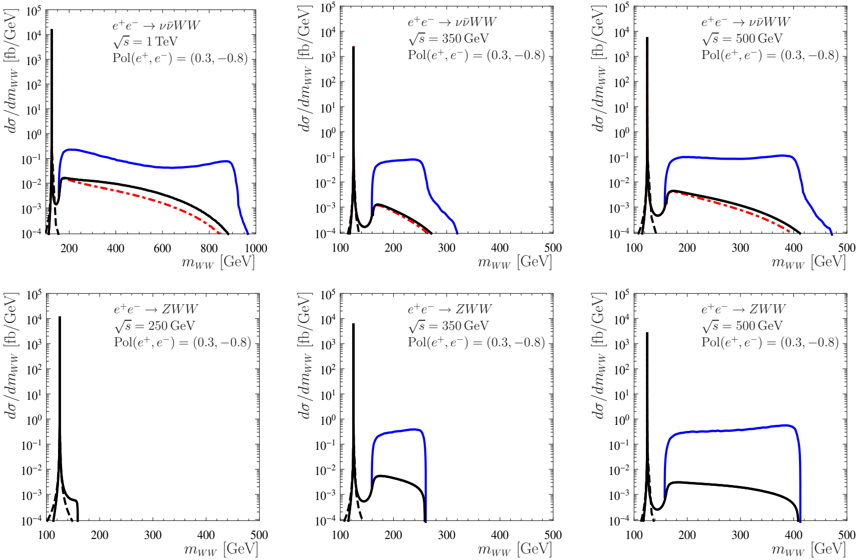
S. Liebler, G. Moortgat-Pick, G. Weiglein (2014), arXiv:1502.07970





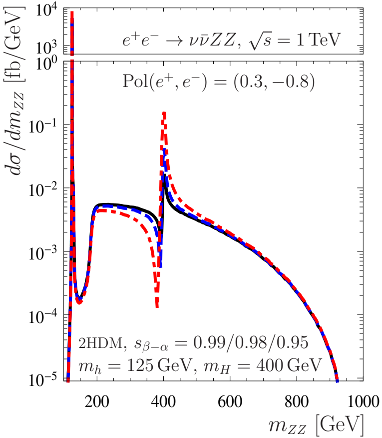
High-mass $H \to VV$ signal at a linear collider

S. Liebler, G. Moortgat-Pick, G. Weiglein (2014), arXiv:1502.07970



Heavy Higgs-light Higgs interference at a linear collider

S. Liebler, G. Moortgat-Pick, G. Weiglein (2014), arXiv:1502.07970



also: N. Greiner, S. Liebler, G. Weiglein, Interference contributions to gluon initiated heavy Higgs production in the 2HDM, arxiv:1512.07232

LHCHXSWG YR4: Off-shell Higgs and Higgs interference

		$gg(\to H) \to \ell\bar{\ell}\ell'\bar{\ell}'$ PDF set order						
Reg.	Amp.	**NLO**	NNLO	R	LO(0.118)	R	LO(0.130)	R
	S	$0.1266(1)$	$0.1255(1)$	$0.991(2)$	$0.1255(1)$	$0.992(2)$	$0.1414(2)$	$1.116(2)$
OFS	$S+I$	$-0.1313(2)$	$-0.1298(2)$	$0.988(2)$	$-0.1307(2)$	$0.995(2)$	$-0.149(1)$	$1.138(8)$
	B	$2.988(4)$	$2.945(5)$	$0.986(2)$	$2.960(4)$	$0.991(2)$	$3.448(5)$	$1.154(3)$
	S	$0.01933(4)$	$0.01906(4)$	$0.986(3)$	$0.01899(4)$	$0.982(3)$	$0.02210(5)$	$1.143(4)$
HM1	$S+I$	$-0.04550(8)$	$-0.04475(8)$	$0.984(3)$	$-0.04486(7)$	$0.986(3)$	$-0.0516(6)$	$1.13(2)$
	B	$1.182(3)$	$1.165(3)$	$0.985(3)$	$1.166(3)$	$0.986(3)$	$1.354(3)$	$1.145(4)$
	S	$0.0981(1)$	$0.0974(1)$	$0.993(2)$	$0.0973(1)$	$0.992(2)$	$0.1084(2)$	$1.105(2)$
HM2	$S+I$	$-0.0465(1)$	$-0.04622(9)$	$0.994(3)$	$-0.04637(9)$	$0.997(3)$	$-0.0522(6)$	$1.12(2)$
	B	$0.611(2)$	$0.605(2)$	$0.990(4)$	$0.598(2)$	$0.980(4)$	$0.676(2)$	$1.107(5)$
	S	$0.800(1)$	$0.780(1)$	$0.976(2)$	$0.843(1)$	$1.054(2)$	$1.021(2)$	$1.276(3)$
RES	$S+I$	$0.803(2)$	$0.784(2)$	$0.976(4)$	$0.845(4)$	$1.052(6)$	$1.023(3)$	$1.274(5)$
	B	$0.1092(2)$	$0.1063(2)$	$0.974(2)$	$0.1150(2)$	$1.053(3)$	$0.1389(2)$	$1.272(3)$
OFS/	S	$0.1583(3)$	$0.1609(3)$		$0.1490(3)$		$0.1385(3)$	
RES	$S+I$	$-0.1635(4)$	$-0.1655(5)$		$-0.1547(7)$		$-0.146(2)$	
HM1/	S	$0.02418(6)$	$0.02443(6)$		$0.02253(6)$		$0.02165(5)$	
RES	$S+I$	$-0.0566(2)$	$-0.0571(2)$		$-0.0531(3)$		$-0.0504(6)$	
HM2/	S	$0.1227(2)$	$0.1249(3)$		$0.1155(2)$		$0.1062(2)$	
RES	$S+I$	$-0.0579(2)$	$-0.0589(2)$		$-0.0549(3)$		$-0.0510(6)$	

LHCHXSWG YR4: Off-shell Higgs and Higgs interference

		Dynamic scale			Fixed scales			
Reg.	Amp.	$M_{2\ell 2\ell}/2$	$\Delta(M_{2\ell 2\ell})$ $\Delta(M_{2\ell 2\ell}/4)$ symmetr. Δ	R R R	$M_H/2$	R	M_Z	R
	S		$-0.0258(2)$	$-0.204(2)$				
	S	$0.1266(1)$	$0.0349(2)$	$0.276(2)$	$0.2038(2)$	$1.610(2)$	$0.1760(2)$	$1.390(2)$
	S		$\pm 0.0303(2)$	$\pm 0.240(1)$				
	$S+I$		$0.0251(2)$	$0.182(2)$				
OFS	$S+I$	$-0.1313(2)$	$-0.0328(2)$	$-0.250(2)$	$-0.1831(2)$	$1.394(2)$	$-0.1604(2)$	$1.221(2)$
	$S+I$		$\pm 0.0290(2)$	$\pm 0.221(1)$				
	B		$-0.545(5)$	$-0.182(2)$				
	B	$2.988(4)$	$0.699(7)$	$0.234(3)$	$3.751(4)$	$1.255(3)$	$3.327(4)$	$1.114(2)$
	B		$\pm 0.6225(4)$	$\pm 0.209(2)$				
	S		$-0.00355(4)$	$-0.184(3)$				
	S	$0.01928(3)$	$0.00455(6)$	$0.236(3)$	$0.02406(6)$	$1.248(4)$	$0.02150(5)$	$1.115(3)$
	S		$\pm 0.00405(4)$	$\pm 0.210(2)$				
	$S+I$		$0.0085(1)$	$0.187(3)$				
HM1	$S+I$	$-0.04553(8)$	$-0.0106(2)$	$-0.233(3)$	$-0.0561(1)$	$1.233(3)$	$-0.05002(9)$	$1.099(3)$
	$S+I$		$\pm 0.0096(1)$	$\pm 0.2095(2)$				
	B		$-0.223(4)$	$-0.188(3)$				
	B	$1.186(3)$	$0.273(5)$	$0.230(4)$	$1.462(3)$	$1.232(4)$	$1.302(3)$	$1.098(4)$
	B		$\pm 0.248(2)$	$\pm 0.209(3)$				
	S		$-0.0207(2)$	$-0.211(2)$				
	S	$0.0982(2)$	$0.0284(2)$	$0.289(2)$	$0.1693(2)$	$1.724(3)$	$0.1451(2)$	$1.478(3)$
	S		$\pm 0.0246(2)$	$\pm 0.250(2)$				
	$S+I$		$0.0099(2)$	$0.212(3)$				
HM2	$S+I$	$-0.04651(8)$	$-0.0136(2)$	$-0.293(3)$	$-0.0818(2)$	$1.760(5)$	$-0.0700(2)$	$1.505(4)$
	$S+I$		$\pm 0.0118(1)$	$\pm 0.253(2)$				
	B		$-0.123(2)$	$-0.201(3)$				
	B	$0.610(1)$	$0.167(3)$	$0.275(5)$	$0.929(3)$	$1.524(5)$	$0.807(2)$	$1.323(4)$
	B		$\pm 0.145(2)$	$\pm 0.238(3)$				
	S		$-0.115(2)$	$-0.143(2)$				
	S	$0.800(1)$	$0.131(2)$	$0.164(2)$	$0.801(2)$	$1.001(2)$	$0.737(1)$	$0.921(2)$
	S		$\pm 0.123(2)$	$\pm 0.154(2)$				
	$S+I$		$-0.116(3)$	$-0.145(2)$				
RES	$S+I$	$0.803(2)$	$0.130(3)$	$0.162(3)$	$0.803(2)$	$1.000(3)$	$0.739(2)$	$0.920(3)$

LHCHXSWG YR4: Off-shell Higgs and Higgs interference

$gg \to H \to VV \to 4$ leptons σ [fb], LHC, $\sqrt{s} = 13$ TeV min. cuts			
final state	S	S+I	gg bkg.
$\ell\bar{\ell}\ell'\bar{\ell}'$	$0.9284(7)$	$0.6707(8)$	$4.264(2)$
$\ell\bar{\ell}\ell\bar{\ell}$	$0.4739(8)$	$0.3467(8)$	$1.723(3)$
$\ell\bar{\ell}\nu_{\ell'}\bar{\nu}_{\ell'}$	$1.896(2)$	$1.386(2)$	$5.730(5)$
$\bar{\ell}\nu_{\ell}\bar{\nu}_{\ell'}\ell'$	$37.95(4)$	$33.60(4)$	$45.31(4)$
$\bar{\ell}\nu_{\ell}\bar{\nu}_{\ell}\ell$	36.01(3)	$31.19(3)$	$50.52(4)$

$gg \to H \to VV \to$ semilept. final states σ [fb], LHC, $\sqrt{s} = 13$ TeV min. cuts			
final state	S	S+I	gg bkg.
$\ell\bar{\ell}d\bar{d}$	$1.711(3)$	$0.96(1)$	$1.575(6)\cdot 10^3$
$\ell\bar{\ell}u\bar{u}$	$1.334(3)$	$0.750(5)$	$2.30(5)\cdot 10^3$
$\ell\bar{\nu}_{\ell}u\bar{d}$	$38.66(5)$	$30.58(8)$	$1.111(3)\cdot 10^4$
$\bar{\ell}\nu_{\ell}\bar{u}d$	$38.68(5)$	$30.59(8)$	$1.112(3)\cdot 10^4$

Summary

- $H \to ZZ, WW$ in ggF & VBF @ LHC: $\mathcal{O}(10\%)$ off-shell high-mass Higgs signal contribution with large Higgs(-Higgs)-continuum interference: now taken into account, provides complementary physics information (similar at high-energy linear collider)
- $gg \to H \to ZZ, WW \to 2\ell 2\ell,\ 4\ell,\ 2\ell 2\nu$: interference studied in great detail, tools & events available (caveat: LO); NLO calculation: technically hard, impressive progress
- Semileptonic channels $gg \to H \to WW \to \ell\nu q q'$ and $gg \to H \to ZZ \to \ell\bar{\ell} q\bar{q}$ contribute to ongoing (heavy) Higgs analyses; first analysis of interference effects in semileptonic channels, new feature: interfering tree-level background
- First analysis of interference (& Higgs width bounds) for $pp \to H \to ZZ$ + jet
- First analysis of heavy Higgs-light Higgs-bkg. interference effects in $gg \to H \to VV$, complementary studies for VBF and linear collider
- Direct Higgs width measurement at LHC limited by mass resolution: $\Gamma_H < 600\ \Gamma_H^{SM}$
- high-mass Higgs tail not Higgs width dependent $\longrightarrow$ provides complementary constraints on Higgs couplings and Higgs width Γ_H (when combined with on-peak data)
- Assuming no E-dependence of relevant Higgs couplings, a bound on Γ_H can be obtained; optimise bound with fully differential discriminant (Matrix Element Method)
- LHC Run 1: CMS: $\Gamma_H < 5.4\ \Gamma_H^{SM}$, ATLAS: $\Gamma_H < [4.5, 7.5]\ \Gamma_H^{SM}$ (95% CL)
- $H \to \gamma\gamma$: interference-facilitated bound $\Gamma_H < 15\ \Gamma_H^{SM}$ (14 TeV, 3 ab^{-1}, 95% CL)
- LHC Run 2: improved bounds (ggF & VBF), high-mass $H \to VV$ EFT and BSM benchmark studies