$H \to VV$ signal-background interference and heavy Higgs line-shape update

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HXSWG Joint Off-Shell and Heavy Higgs Discussion
CERN
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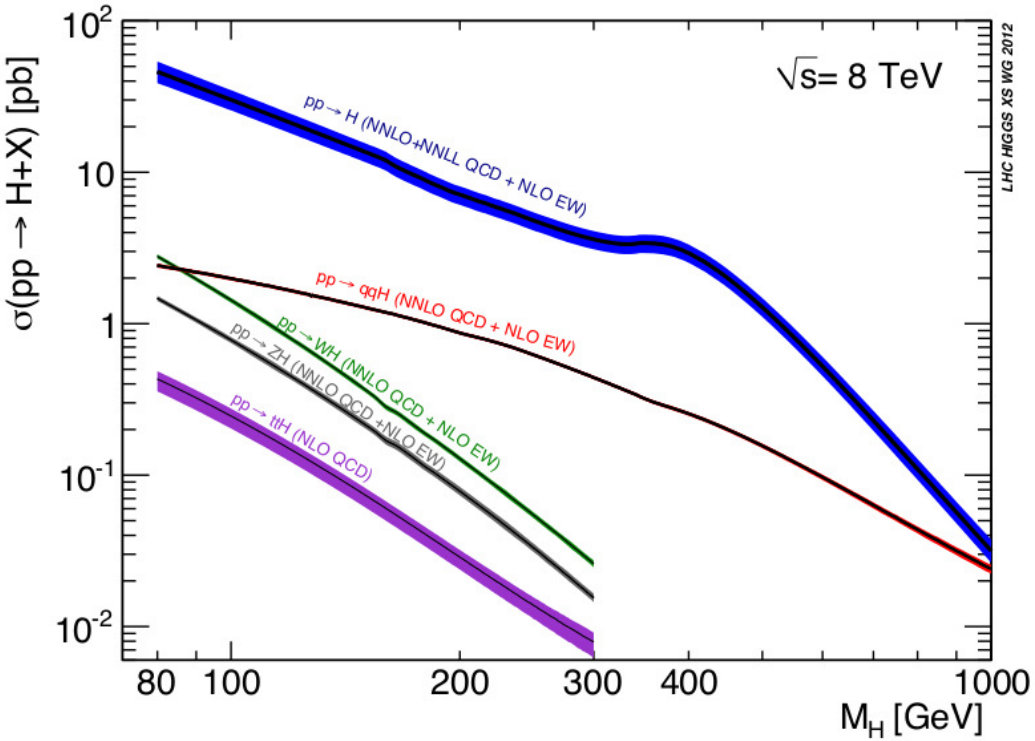
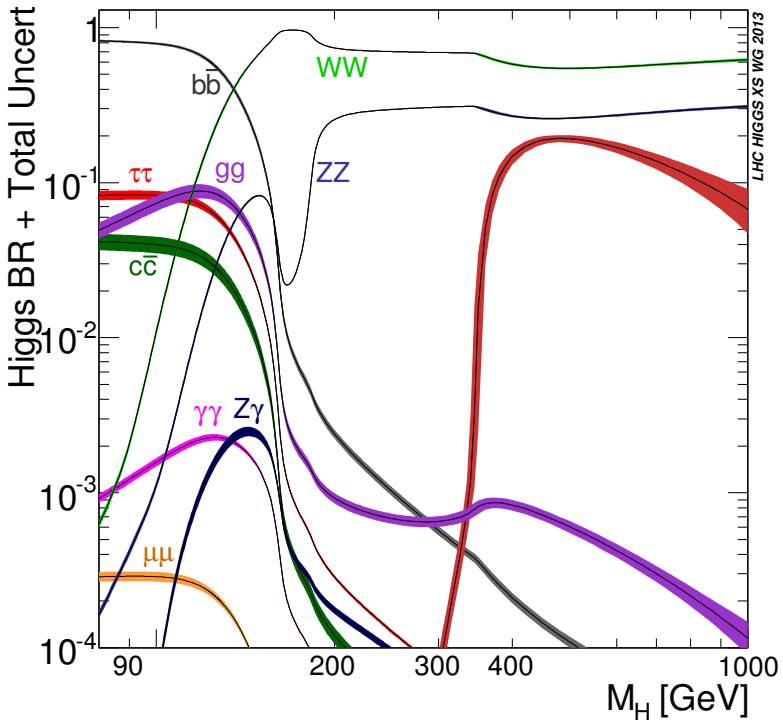
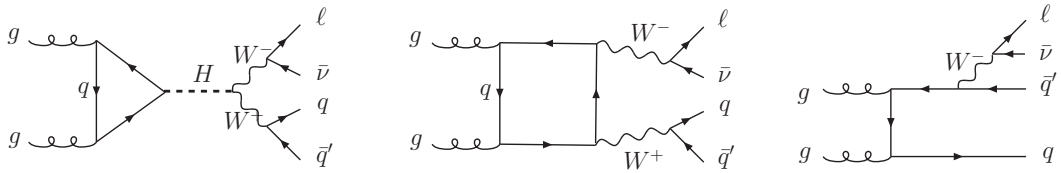
SM Higgs boson production and decay at the LHC





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. (NLO 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

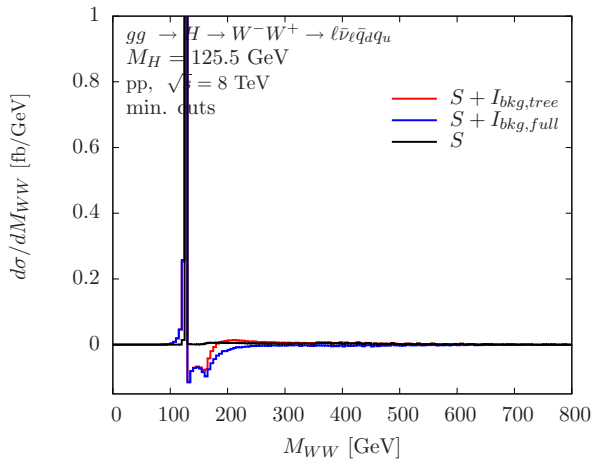
$gg \to H \to ZZ \to \ell\bar{\ell}q_u\bar{q}_u$ σ [fb], pp, $\sqrt{s} = 8$ TeV		interference			ratio		
cuts	S	I_{tree}	I_{loop}	I_{full}	R_{tree}	R_{loop}	R_{full}
min.	1.96(1)	–0.190(4)	–0.343(3)	–0.541(5)	0.903(7)	0.825(7)	0.724(7)
LHC	0.1166(6)	0.017(2)	–0.194(2)	–0.176(6)	1.15(2)	–0.67(2)	–0.51(5)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

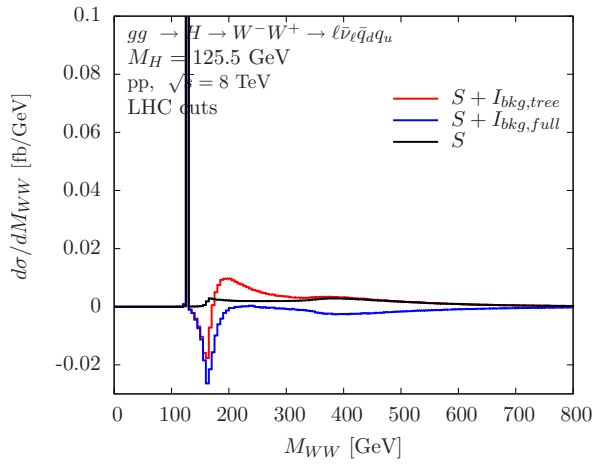
$gg \to H \to ZZ \to \ell\bar{\ell}q_d\bar{q}_d$ σ [fb], pp, $\sqrt{s} = 8$ TeV		interference			ratio		
cuts	S	I_{tree}	I_{loop}	I_{full}	R_{tree}	R_{loop}	R_{full}
min.	2.51(2)	–0.248(3)	–0.439(6)	–0.680(7)	0.901(7)	0.825(7)	0.729(7)
LHC	0.1497(8)	0.0223(6)	–0.245(5)	–0.227(3)	1.149(9)	–0.64(3)	–0.52(2)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

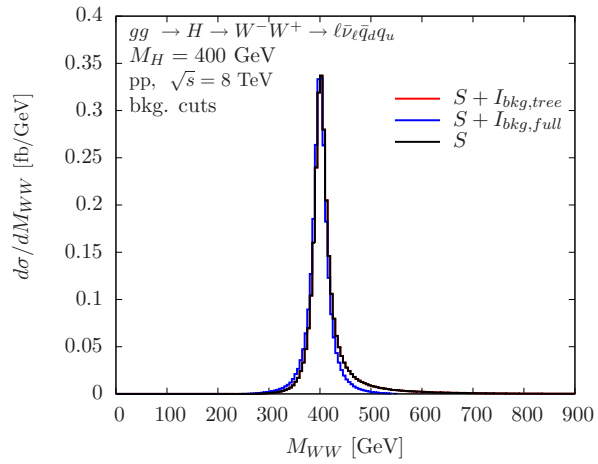
higher-order background contributions can induce leading interference effects

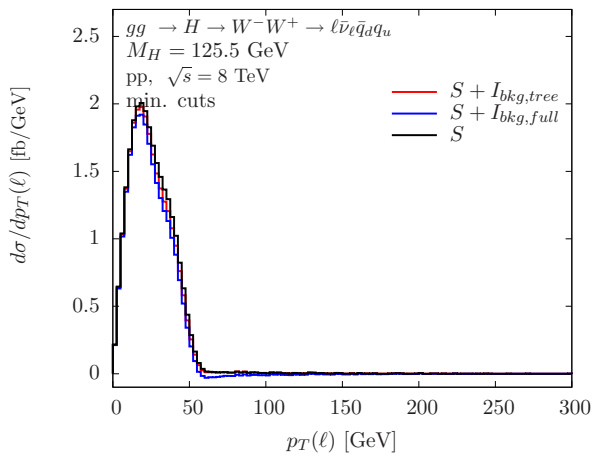
NK, O'Brien, Vryonidou (gg2VV, MadGraph5_aMC@NLO) arXiv:1506.01694

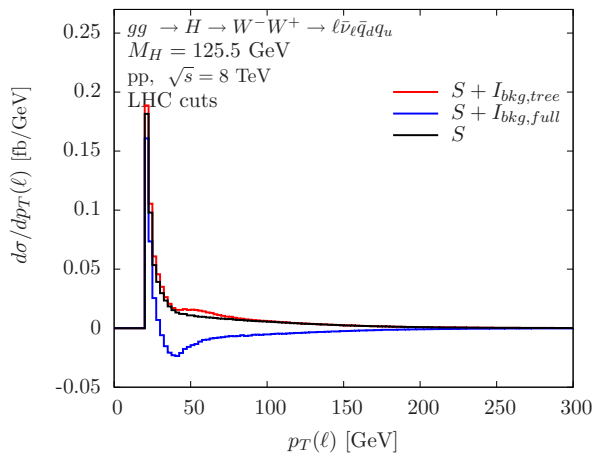
Interference for semileptonic H decay modes in ggF

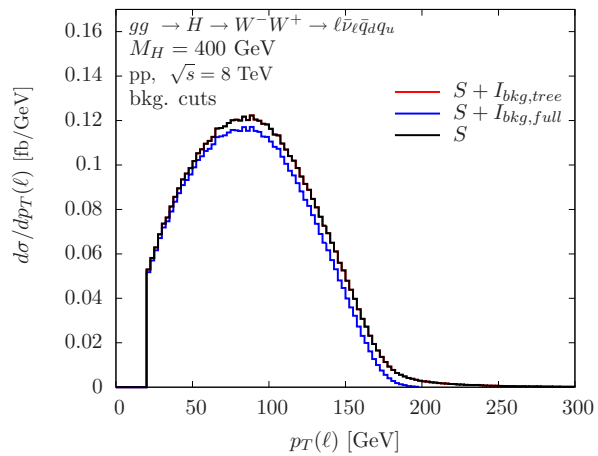






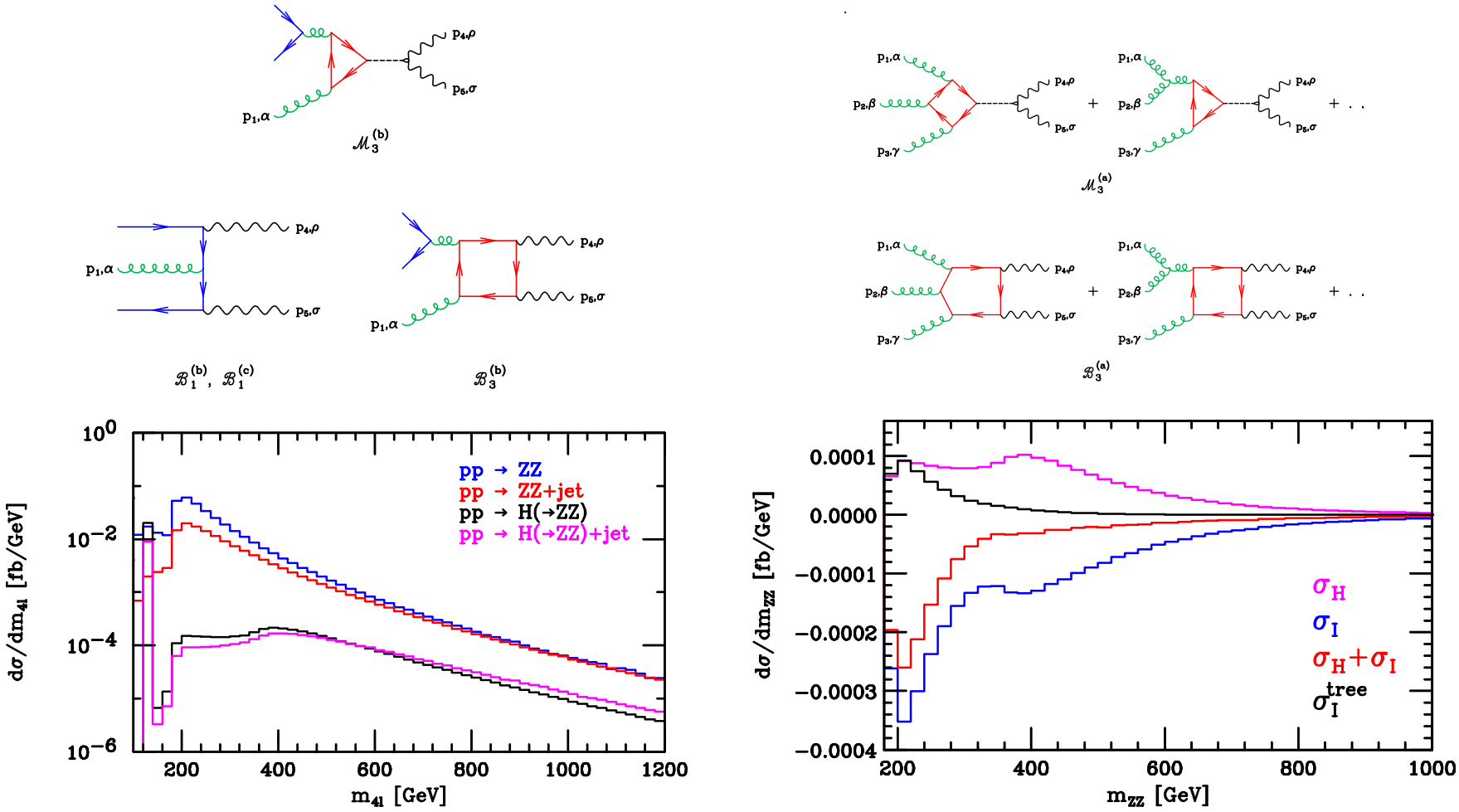






NK, O'Brien, Vryonidou 1506.01694

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



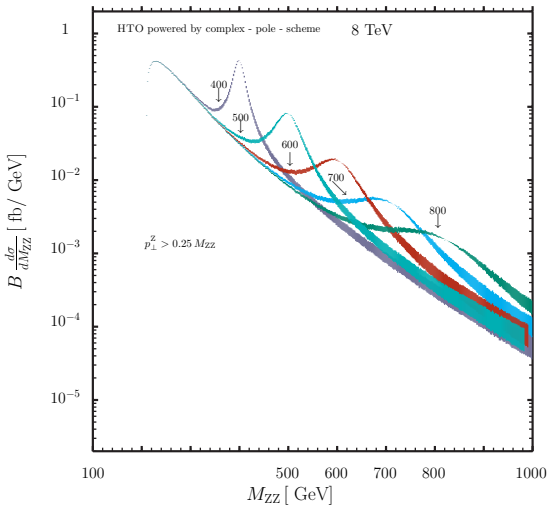
off-shell Higgs cross sections for ZZ and ZZ+jet comparable ($p_{Tj} > 30$ GeV)

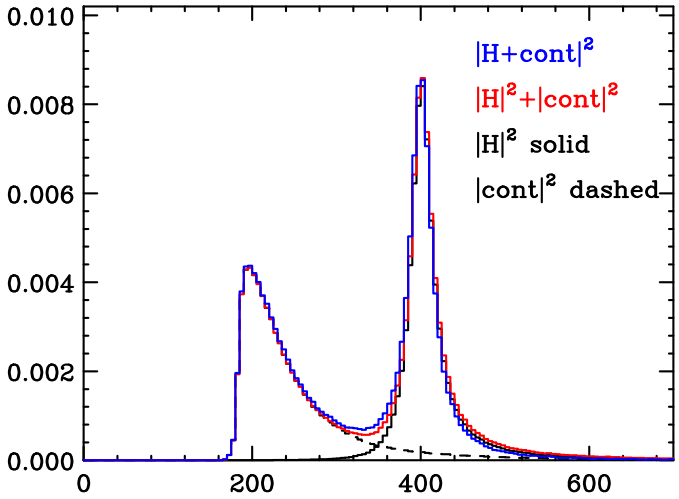
Campbell, Ellis, Furlan, Röntsch figures taken from 1409.1897

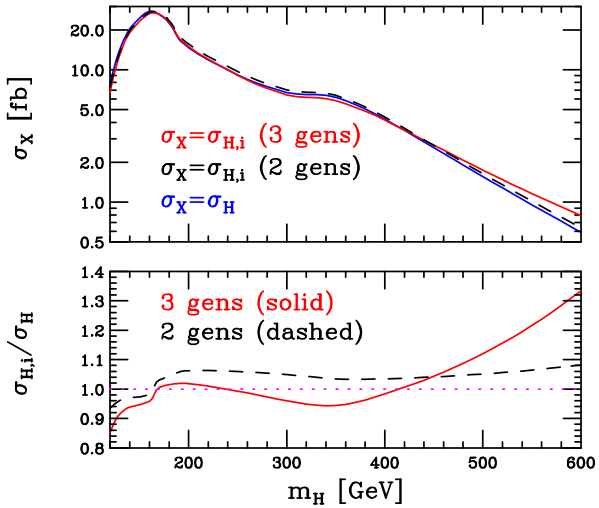
Z bosons treated in zero-width approximation (validated for ZZ final state: excellent for $m_{4l} > 300$ GeV)

Heavy Standard Model Higgs - continuum VV interference

$gg \to H \to ZZ, WW \to 4$ leptons and $gg \to ZZ, WW \to 4$ leptons cont. bkg.







Passarino 1206.3824 (ZZ), NK 1206.3824 (ZZ), Campbell, Ellis, Williams 1107.5569 (WW)

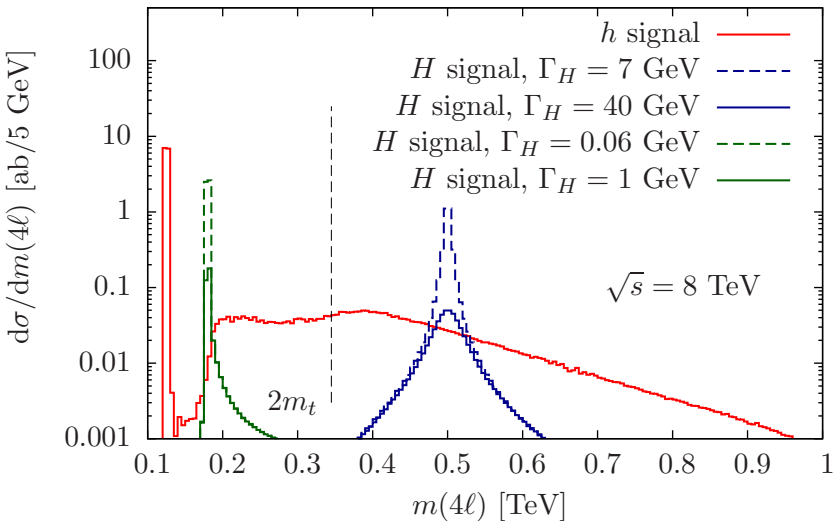
see also: Bonvini, Caola, Forte, Melnikov, Ridolfi, 1304.3053; NK, 1310.7011; Moult, Stewart, 1405.5534; Campanario, Li, Rauch, Spira, 1211.5429

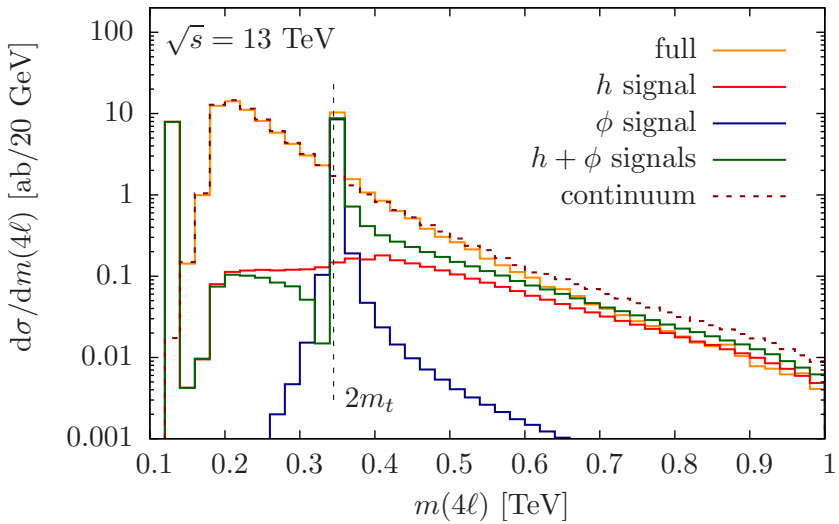
heavy SM Higgs no longer compatible with data

Heavy Higgs - light Higgs - continuum VV interference

consider 1-Higgs-Singlet extension of SM, Higgs portal model, ...

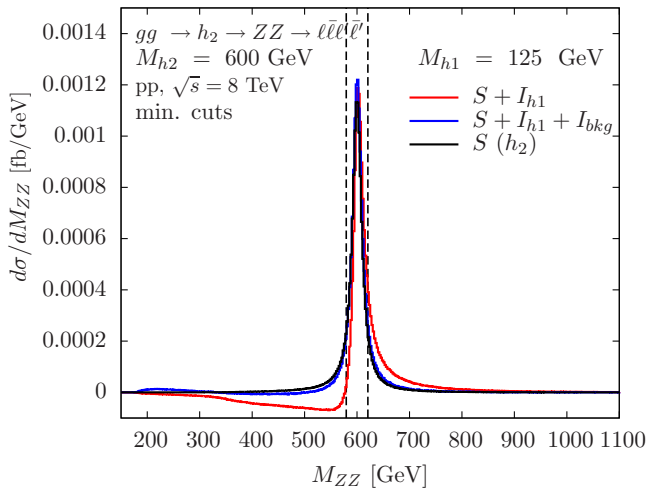
$$gg\ (\to \{h_1, h_2\}) \to ZZ, WW \to 4 \text{ leptons}$$

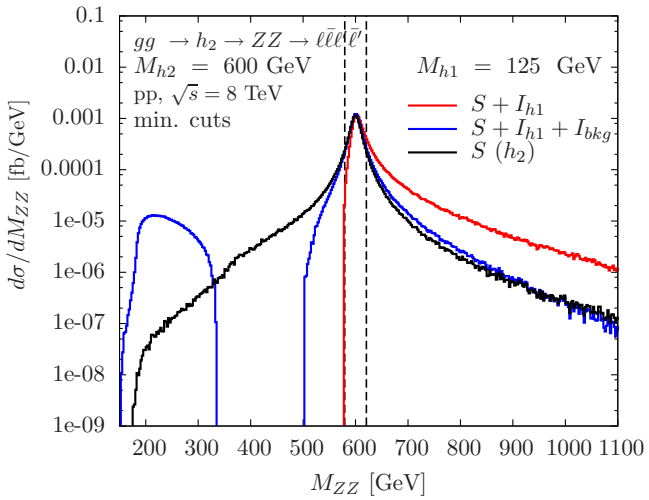




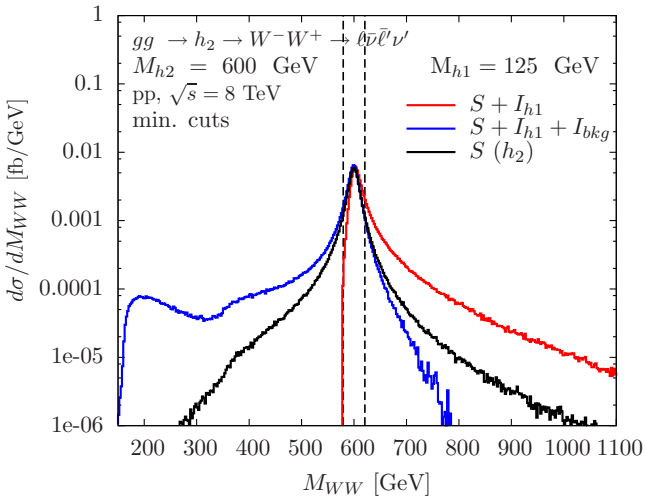
Englert, Low, Spannowsky 1502.04678; Englert, Soreq, Spannowsky 1410.5440

Heavy Higgs - light Higgs - continuum VV interference

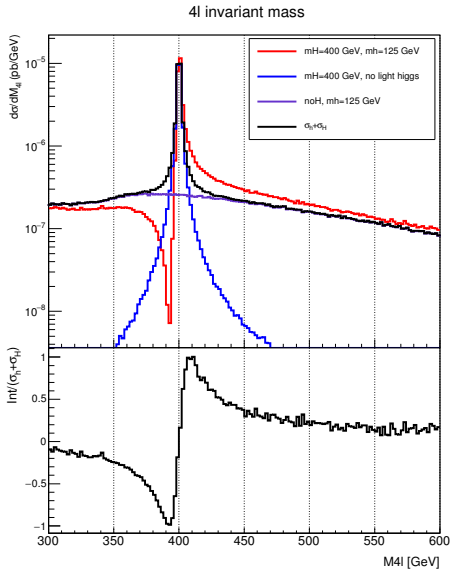


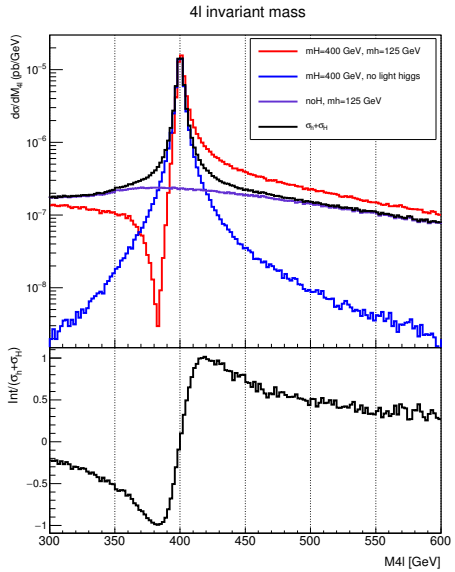


NK, O'Brien 1502.04113



NK, O'Brien 1502.04113





Maina 1501.02139

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 1307.1347, Sec. 13.3

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

NK, O'Brien (gg2VV) 1502.04113

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

$gg \to h_2 \to ZZ \to \ell\bar{\ell}\ell'\bar{\ell}'$ σ [fb], pp, $\sqrt{s} = 8$ TeV min. cuts, $\theta = \pi/15$		interference			ratio		
M_{h2} [GeV]	S	I_{h1}	I_{bkg}	I_{full}	R_{h1}	R_{bkg}	R_{full}
300	0.033453(7)	0.00392(2)	0.00105(2)	0.00499(2)	1.1171(6)	1.0315(7)	1.1492(6)
600	0.005223(4)	-0.001738(8)	0.001730(9)	-9(4)e-06	0.667(2)	1.331(2)	0.998(2)
900	0.0005088(4)	-0.001151(2)	0.001043(3)	-0.0001092(9)	-1.263(5)	3.049(5)	0.785(2)

Cross sections for $gg\ (\to \{h_1, h_2\}) \to ZZ \to \ell\bar{\ell}\ell'\bar{\ell}'$ in pp collisions at $\sqrt{s} = 8$ TeV at loop-induced leading order in the 1-Higgs-Singlet Extension of the SM with $M_{h1} = 125$ GeV, $M_{h2} = 300, 600, 900$ GeV and mixing angle $\theta = \pi/15$. Results for the heavy Higgs (h_2) signal (S) and its interference with the light Higgs (I_{h1}) and the continuum background (I_{bkg}) and the full interference (I_{full}) are given. The ratio $\boldsymbol{R_i = (S + I_i)/S}$ illustrates the relative change of the heavy Higgs signal due to interference with the light Higgs and continuum background amplitude contributions. Minimal cuts are applied: $M_{\ell\bar{\ell}} > 4$ GeV, $M_{\ell'\bar{\ell}'} > 4$ GeV, $p_{TV} > 1$ GeV. Cross sections are given for a single lepton flavour combination.

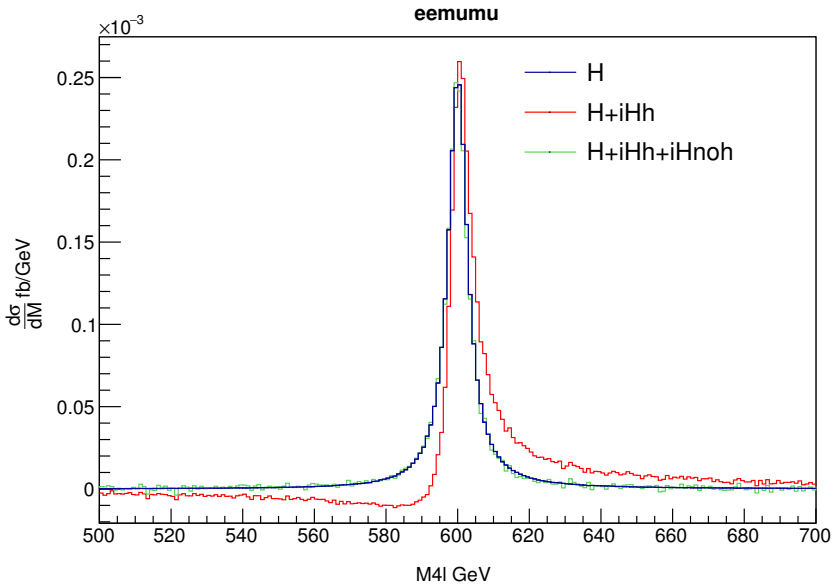
Heavy Higgs - light Higgs - continuum VV interference

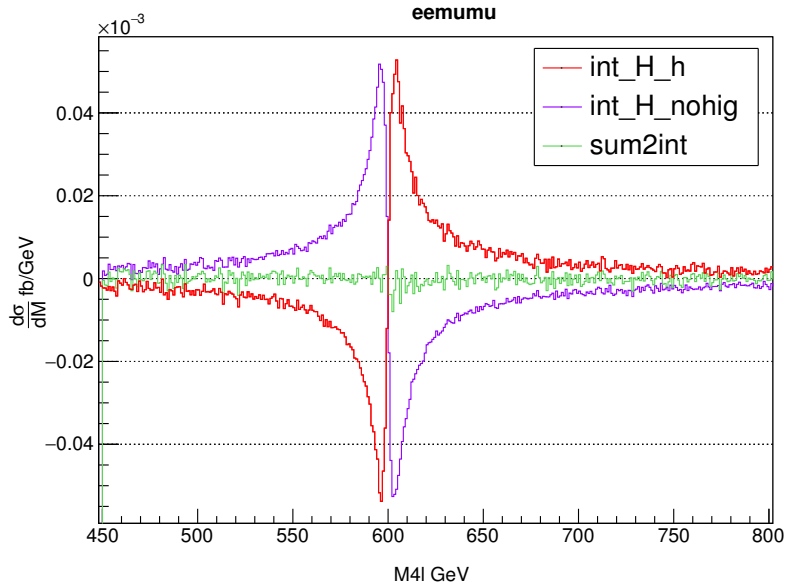
$gg \to h_2 \to ZZ \to \ell\bar{\ell}\ell'\bar{\ell}'$ σ [fb], pp, $\sqrt{s} = 8$ TeV min. cuts, $\theta = \pi/8$		interference			ratio		
M_{h2} [GeV]	S	I_{h1}	I_{bkg}	I_{full}	R_{h1}	R_{bkg}	R_{full}
300	0.12209(9)	0.0119(1)	0.00358(5)	0.01545(4)	1.097(2)	1.029(2)	1.127(2)
600	0.01821(2)	-0.00498(2)	0.00568(2)	0.000694(8)	0.727(2)	1.312(2)	1.038(2)
900	0.001781(2)	-0.003277(5)	0.003396(5)	0.000118(3)	-0.840(3)	2.906(4)	1.066(2)

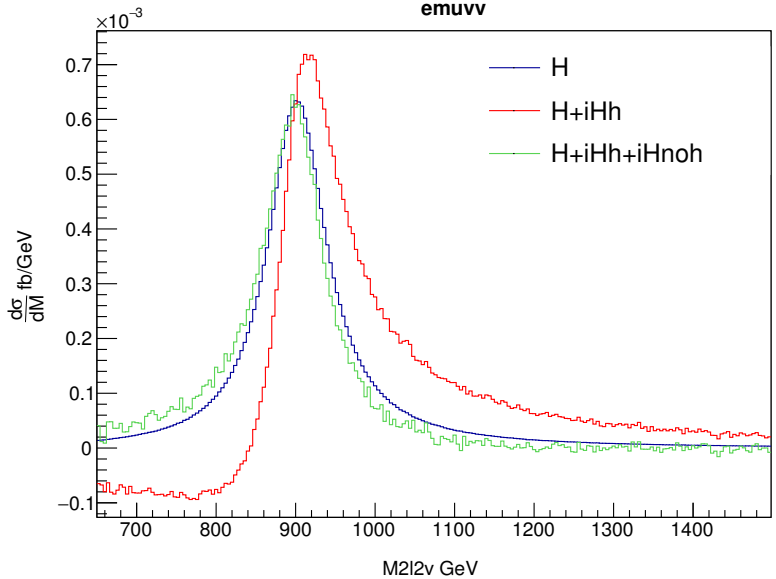
$gg \to h_2 \to ZZ \to \ell\bar{\ell}\ell'\bar{\ell}'$ σ [fb], pp, $\sqrt{s} = 8$ TeV min. cuts & $\lvert M_{VV} - M_{h2}\rvert < \Gamma_{h2}$ $\theta = \pi/8$		interference			ratio		
M_{h2} [GeV]	S	I_{h1}	I_{bkg}	I_{full}	R_{h1}	R_{bkg}	R_{full}
300	0.08537(8)	3.6(4)e-05	0.005371(9)	0.00541(1)	1.000(2)	1.063(2)	1.063(2)
600	0.01323(2)	-0.000174(4)	0.001058(4)	0.000884(6)	0.987(2)	1.080(2)	1.067(2)
900	0.001283(1)	-0.0001316(9)	0.000373(1)	0.000241(2)	0.897(2)	1.290(2)	1.188(2)

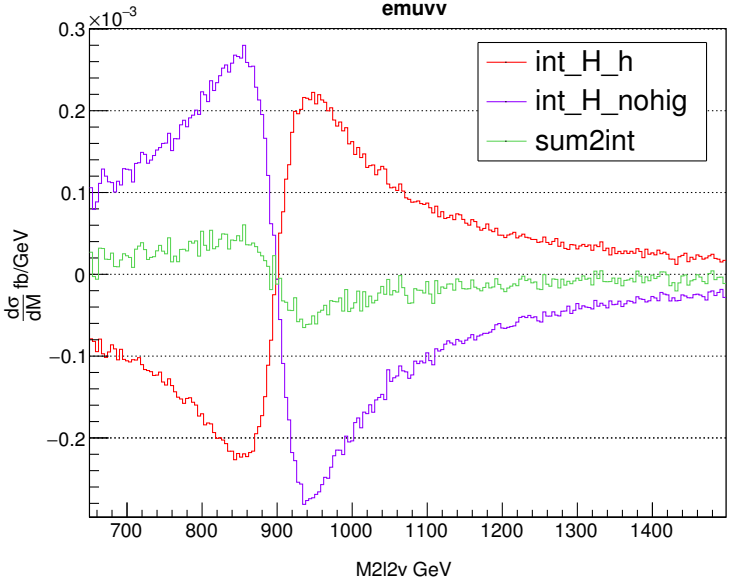
Heavy Higgs interference in Vector Boson Fusion

Ballestrero, Maina (PHANTOM) 1506.02257 (see also: Rauch, Schissler (VBFNLO) 1307.1347, Sec. 12.4)









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 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 hep-ph/0604011 (also 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 1405.2219 and T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhofer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi 1408.5243

$gg \to VV$ enters $pp \to VV$ at NNLO QCD $\to$ LO (loop-induced) with $\sim$ 20–25% scale uncertainty, unknown NLO K-factor, but expected to be similar to signal, i.e. ~ 1.6

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

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

$\to$ NLO $gg \to VV$ correction is of similar size or larger than residual $pp \to VV$ scale uncertainty $\Rightarrow$ calculation is important and by a similar argument the calculation of the NLO 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:

M. Bonvini, F. Caola, S. Forte, K. Melnikov, G. Ridolfi 1304.3053:

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)
$\to$ interference K-factors are generally very similar to signal K-factors (also for kinematic distributions)

C. Li, H. Li, D. Shao, J. Wang 1504.02388:

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

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 1503.08759

A. v. Manteuffel, L. Tancredi 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 1503.01274