Inadequacy of zero-width approximation for a light Higgs boson signal

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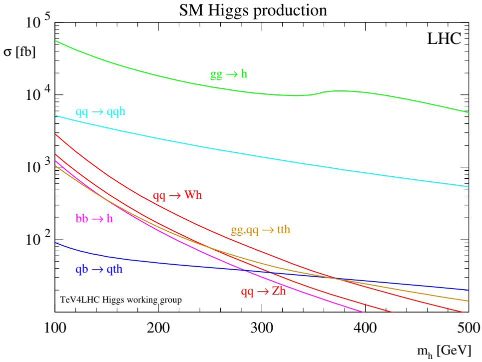
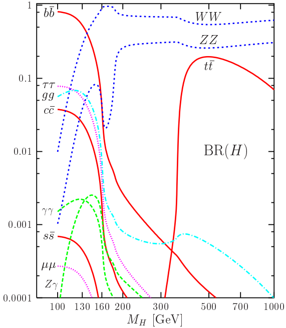
Outline

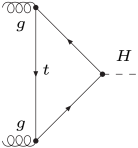
Higgs boson production and decay at the LHC





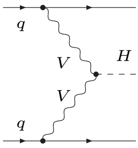
Gluon fusion:

$(gg \to H)$



Weak boson fusion:

$(qq \to Hqq,\ V = W, Z)$



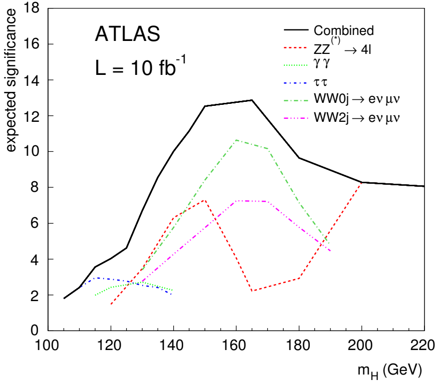
Dominant decay modes:

$H \to b\bar{b}$ for $M_H \lesssim$ 135 GeV

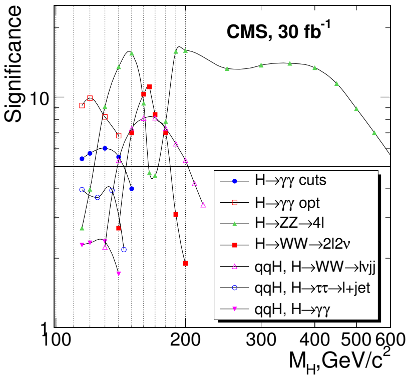
$H \to WW, ZZ$ for $M_H \gtrsim$ 135 GeV

source: Tevatron-for-LHC Higgs Report (2007), Djouadi (2005)

LHC discovery potential for the SM Higgs boson



ATLAS Physics TDR 2008, $\sqrt{s}$ =14 TeV



CMS Physics TDR 2006, $\sqrt{s}$ =14 TeV

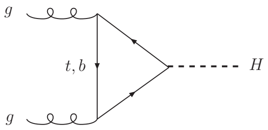
06/03/2013 ATLAS & CMS: $> 5\sigma$ SM Higgs boson at ∼126 GeV ($5.1\,\text{fb}^{-1}$@7TeV + $19.6\,\text{fb}^{-1}$@8TeV)

04/07/2012 ATLAS & CMS: 5σ excess at 125-126 GeV compatible with SM Higgs boson (5–$10\,\text{fb}^{-1}$)

13/12/2011 7 TeV data, $\approx 5\,\text{fb}^{-1}$ p. exp., ATLAS: $M_H \in [116, 130]$ GeV, CMS: $M_H \in [115, 127]$ GeV

LEP: $M_H > 114.4$ GeV, $M_H = 89^{+35}_{-26}$ $(< 158, 185)$ GeV, Tevatron: $M_H \notin [158, 175]$ GeV

Gluon-fusion Higgs production



Leading order (LO), loop-induced Georgi, Glashow, Machacek, Nanopoulos (1978)

Next-to-leading order (NLO), $m_t \to \infty$ approx. (few percent accuracy) Djouadi, Spira, Zerwas (1991); Dawson (1991)

NLO, full m_t, m_b dependence, LHC: $K - 1 \sim$ 80–100% Graudenz, Spira, Zerwas (1993); Spira, Djouadi, Graudenz, Zerwas (1995)

Next-to-next-to-leading order (NNLO), $m_t \to \infty$ approx., NNLO/NLO – 1 $\sim$ 25% Harlander (2000); Catani, de Florian, Grazzini (2001); Harlander, Kilgore (2001, 2002); Anastasiou, Melnikov (2002); Ravindran, Smith, van Neerven (2003); Blümlein, Ravindran (2005); Catani, Grazzini (2007)

soft-gluon resummation, $\leq$NNLL, + 7–9%(6–7%) at 7(14) TeV Catani, de Florian, Grazzini, Nason (2003)

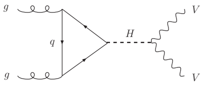
leading soft contributions @ NNNLO Moch, Vogt (2005); Laenen, Magnea (2006); Idilbi, Ji, Ma, Yuan (2006); Ravindran (2006)

accuracy of $m_t \to \infty$ approx. @ NNLO (<1% if $M_H \lesssim$ 300 GeV) Marzani, Ball, Del Duca, Forte, Vicini (2008); Harlander, Ozeren (2009); Harlander, Mantler, Marzani, Ozeren (2010); Pak, Rogal, Steinhauser (2009, 2010); Anastasiou, Boughezal, Petriello (2009)

Electroweak corrections: +5% (M_H = 120 GeV) to –2% (M_H = 300 GeV) Djouadi, Gambino (1994); Aglietti, Bonciani, Degrassi, Vicini (2004); Degrassi, Maltoni (2004); Actis, Passarino, Sturm, Uccirati (2009); Actis, Passarino, Sturm, Uccirati (2008); Anastasiou, Boughezal, Petriello (2008); Keung, Petriello (2009); Brein (2010)

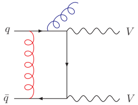
Recent updates de Florian, Grazzini (2009); Baglio, Djouadi (2010, 2011); Baglio, Djouadi, Ferrag, Godbole (2011); Catani, Grazzini (2011); Spira (HIGLU update); de Florian, Ferrera, Grazzini, Tommasini (2011, 2012) (HRes); LHCHXS2 (2012); Anastasiou, Buehler, Herzog, Lazopoulos (2012) (ihixs); de Florian, Grazzini (2012)

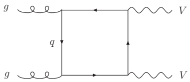
Gluon-fusion Higgs $\to VV$ and continuum VV production



$gg \to H \to VV$ searches Dittmar, Dreiner (1996); Davatz, Giolo-Nicollerat, Zanetti (2006); Mellado, Quayle, Sau Lan Wu (2007); Davatz, Dittmar, Giolo-Nicollerat (2007); Davatz (2007); Quayle (2008); Mellado, Ruan, Zhang (2011)

QCD corrections/shower MCs for $gg \to H \to VV$ searches Cranmer, Mellado, Quayle, Sau Lan Wu (2003); Davatz, Dissertori, Dittmar, Grazzini, Pauss (2004); Davatz, Stöckli, Anastasiou, Dissertori, Dittmar, Melnikov, Petriello (2006); Davatz, Dittmar, Pauss (2006); Grazzini (2006, 2008); Anastasiou, Dissertori, Stöckli (2007); Anastasiou, Dissertori, Stöckli, Webber (2008); Frederix, Grazzini (2008); Anastasiou, Dissertori, Grazzini, Stöckli, Webber (2009)





$q\bar{q} \to VV$ (LO, NLO, decays) Brown, Mikaelian (1979); Stirling, Kleiss, Ellis (1985); Gunion, Kunszt (1986); Muta, Najima, Wakaizumi (1986); Berends, Kleiss, Pittau (1994); Ohnemus (1991); Mele, Nason, Ridolfi (1991); Ohnemus, Owens (1991); Frixione (1993); Ohnemus (1994); Dixon, Kunszt, Signer (1998, 1999); Campbell, Ellis (1999) (MCFM); Campbell, Ellis, Williams (2011) (MCFM); Melia, Nason, Röntsch, Zanderighi (2011) (POWHEG BOX)

$gg \to VV$ and $gg \to VVg$ [loop induced] (LO, decays) Dicus, Kao, Repko (1987); Glover, van der Bij (1989); Kao, Dicus (1991); Matsuura, v.d. Bij (1991); Zecher, Matsuura, v.d. Bij (1994); Dührssen, Jakobs, v.d. Bij, Marquard (2005); Binoth, Ciccolini, NK, Krämer (2005, 2006) (gg2WW); Binoth, NK, Mertsch (2008) (gg2ZZ); Campbell, Ellis, Williams (2011) (MCFM); Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli (2011) (aMC@NLO); Melia, Melnikov, Rontsch, Schulze, Zanderighi (2012) (MCFM); NK (2012) (gg2VV); Agrawal, Shivaji (2012); VBFNLO-2.6; Campanario, Li, Rauch, Spira (2012); Frixione, Hirschi, Laureys, Maltoni

Higgs-continuum $VV(g)$ interference Glover, van der Bij (1989); Binoth, Ciccolini, NK, Krämer (2006) (gg2WW); Campbell, Ellis, Williams (2011) (MCFM); NK (2012) (gg2VV); Passarino (2012); NK, Passarino (2012); VBFNLO-2.6; Campanario, Li, Rauch, Spira (2012); Frixione, Hirschi, Laureys, Maltoni; $\gamma\gamma$: Dixon, Siu (2003); Martin (2012); de Florian et al. (2013)

Zero-width approximation
a.k.a. narrow-width approximation

for scalar particle:

$$D(q^2) = \frac{1}{(q^2 - M^2)^2 + \Gamma^2 M^2} = \frac{\pi}{M\,\Gamma}\,\delta\left(q^2 - M^2\right)$$

$$+ \, PV\left[\frac{1}{(q^2 - M^2)^2}\right] + \sum_{n=0}^{N} c_n(\alpha)\,\delta_n\left(q^2 - M^2\right)$$

with $\delta_n(x) := (-1)^n / n!\,\delta^{(n)}(x)$

in limit $\Gamma \to 0$: $\boxed{D(q^2) \sim K\,\delta(q^2 - M^2)}$ with $K = \frac{\pi}{M\Gamma} = \int_{-\infty}^{+\infty} dq^2\, D(q^2)$

common error estimate $\mathcal{O}(\Gamma/M)$ not reliable:

$$\sigma = \frac{1}{2s}\left[\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{dq^2}{2\pi}\left(\int d\phi_p |\mathcal{M}_p(q^2)|^2 D(q^2) \int d\phi_d |\mathcal{M}_d(q^2)|^2\right)\right]$$

$$\sigma_{\text{ZWA}} = \frac{1}{2s}\left(\int d\phi_p |\mathcal{M}_p(M^2)|^2\right)\left(\int_{-\infty}^{\infty} \frac{dq^2}{2\pi}\, D(q^2)\right)\left(\int d\phi_d |\mathcal{M}_d(M^2)|^2\right)$$

$$\sigma_{\text{ZWA}} = \frac{1}{2s}\left(\int d\phi_p |\mathcal{M}_p|^2\right)\frac{1}{2M\Gamma}\left(\int d\phi_d |\mathcal{M}_d|^2\right)\Big|_{q^2=M^2}$$

tails of Breit-Wigner ($\frac{\sigma_{\text{tail}}}{\sigma} \approx \frac{1}{n\pi}$ with $|\sqrt{q^2} - M| > n\Gamma$) are not nearly as suppressed as tails of Gaussian

for $H \to f\bar{f}$: $|\mathcal{M}_d(q^2)|^2 \sim m_f^2 q^2$, for $H \to VV$: $|\mathcal{M}_d(q^2)|^2 \sim (q^2)^2$ for $\sqrt{q^2} \gtrsim 2\,M_V$

Light Higgs: Inclusive analysis

Signal cross section calculated with HTO (Passarino, unpublished):

complex pole, OFFP schemes Goria, Passarino, Rosco (2011); Passarino, Sturm, Uccirati (2010); Actis, Passarino (2006)

$$\sigma_{gg\to H\to ZZ}(M_{ZZ}) = \frac{1}{\pi}\,\sigma_{gg\to H}\,(M_{ZZ})\;\frac{M_{ZZ}^4}{\left|M_{ZZ}^2 - s_H\right|^2}\;\frac{\Gamma_{H\to ZZ}\,(M_{ZZ})}{M_{ZZ}}$$

Higgs complex pole: $s_H = \mu_H^2 - i\,\mu_H\,\gamma_H$

Note: γ_H is not the on-shell width, but numerical difference tiny for light Higgs GPR (2011)

$\sigma_{gg\to H}(M_{ZZ})$: NNLO QCD LHCHXS2 (2012), NLO EW Actis, Passarino, Sturm, Uccirati (2008)

$\Gamma_{H\to ZZ}(M_{ZZ})$: NLO + leading NNLO Bredenstein, Denner, Dittmaier, Weber (2007)

using MSTW2008 PDF sets Martin, Stirling, Thorne, Watt (2009)

$\mu_H = 125$ GeV, $\gamma_H = 4.03$ MeV, $\mu_R = \mu_F = M_{ZZ}$

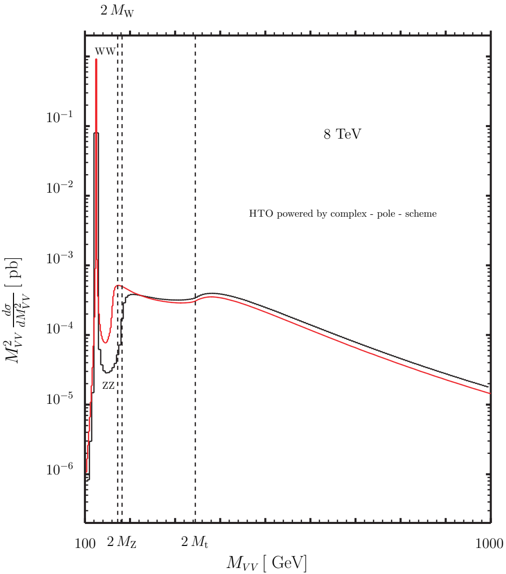
Bar scheme ($\equiv$ complex pole scheme): GPR (2011)

$$\overline{M}_H^2 = \mu_H^2 + \gamma_H^2\,, \qquad \mu_H\,\overline{\Gamma}_H = \overline{M}_H\,\gamma_H\,,$$

$$\frac{1}{M_{ZZ}^2 - s_H} = \left(1 + i\,\frac{\overline{\Gamma}_H}{\overline{M}_H}\right)\left(M_{ZZ}^2 - \overline{M}_H^2 + i\,\frac{\overline{\Gamma}_H}{\overline{M}_H}\,M_{ZZ}^2\right)^{-1}$$

Light Higgs: Inclusive analysis

NNLO $gg \to H \to VV$: VV invariant mass distributions ($V = W, Z$)



Light Higgs: Inclusive analysis

Total cross-sections:

	Tot [pb]	$M_{ZZ} > 2\,M_Z$ [pb]	R
$gg \to H \to$ all	19.146	0.1525	$\mathbf{0.8\%}$
$gg \to H \to ZZ$	0.5462	0.0416	$\mathbf{7.6\%}$

Bin-by-bin integrated cross-section for the process $gg \to H \to ZZ$:

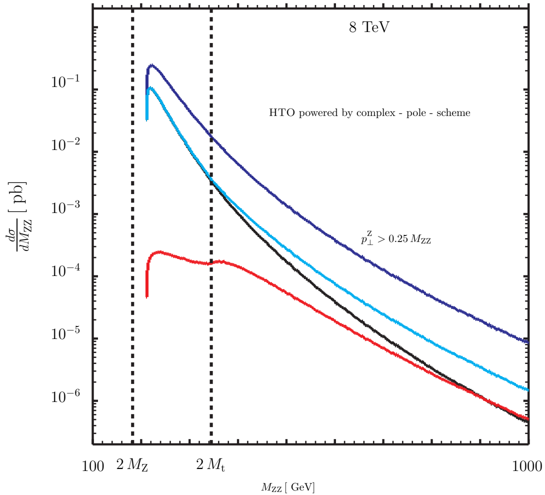
First row: bin in GeV, second row: corresponding cross-section in pb

100–125	125–150	150–175	175–200	200–225	225–250	250–275
0.252	0.252	$0.195 \cdot 10^{-3}$	$0.177 \cdot 10^{-2}$	$0.278 \cdot 10^{-2}$	$0.258 \cdot 10^{-2}$	$0.240 \cdot 10^{-2}$

$gg \to H \to \gamma\gamma$: the effect is drastically reduced and confined to the region $M_{\gamma\gamma}$ between 157 GeV and 168 GeV, where the distribution is already five orders of magnitude below the peak

Light Higgs: Inclusive analysis

$gg\ (\to H)/q\bar{q} \to ZZ$: ZZ invariant mass distributions (μ_H =125 GeV, LO)



gg total (black), signal (red), signal + gg background (cyan), signal + gg and $q\bar{q}$ background (blue)

Light Higgs: Analysis with selection cuts

Calculate $gg \to H \to VV \to$ leptons ($V = W, Z$) cross sections and distributions at LO using gg2VV with Higgs in ZWA as well as off-shell including interference with continuum VV production (γ^* contributions included, important for $M_H < 2M_Z$) including experimental selection cuts.

- pp collisions at $\sqrt{s} = 8$ TeV
- all results for single lepton flavour combination ($\ell^\pm$ and ν)
- input parameters: LHC Higgs Cross Section WG, arXiv:1101.0593 [hep-ph], App. A (with NLO Γ_V and G_μ scheme)
- MSTW2008NNLO PDF
- finite top and bottom quark mass effects included
- $M_H = 125\ (200)$ GeV with $\Gamma_H = 0.004434\ (1.428)$ GeV (HDECAY)
- $\mu_R = \mu_F = M_H/2$
- fixed-width Breit-Wigner for Higgs and V propagators
- $V_{\text{CKM}} = 1$: negligible error ($< 10^{-5}$)

For on/off-shell comparison, define the ZWA M_{VV} distribution as:

$$\left(\frac{d\sigma}{dM_{VV}}\right)_{\text{ZWA}} = \sigma_{H,\text{ZWA}} \frac{M_H\Gamma_H}{\pi} \frac{2M_{VV}}{\left(M_{VV}^2 - M_H^2\right)^2 + (M_H\Gamma_H)^2}$$

ZWA/off-shell and signal-background interference measures

Relative measure for accuracy of ZWA/off-shell effect

$$R_0 := \frac{\sigma_{H,\text{ZWA}}}{\sigma_{H,\text{offshell}}}$$

Relative measures for interference effect

$S + B$-inspired measure:

$$R_1 := \frac{\sigma(|\mathcal{M}_\text{H} + \mathcal{M}_\text{cont}|^2)}{\sigma(|\mathcal{M}_\text{H}|^2) + \sigma(|\mathcal{M}_\text{cont}|^2)}$$

$S/\sqrt{B}$-inspired measure:

$$R_2 := \frac{\sigma(|\mathcal{M}_\text{H}|^2 + 2\,\text{Re}(\mathcal{M}_\text{H}\mathcal{M}^*_\text{cont}))}{\sigma(|\mathcal{M}_\text{H}|^2)}$$

Light Higgs: Analysis with selection cuts

$gg \to H \to ZZ \to \ell\bar{\ell}\ell\bar{\ell}$ and $\ell\bar{\ell}\ell'\bar{\ell}'$ at $M_H = 125$ GeV

Same- and different-flavour 4-charged-lepton channels

In these search channels, the invariant mass of the intermediate Higgs ($M_{H^*} \equiv M_{ZZ}$) can be reconstructed. The M_{ZZ} spectrum is hence used as the discriminant variable in the final stage of the analysis, and the test statistic is evaluated with a binned maximum-likelihood fit of signal and background models to the observed M_{ZZ} distribution. For light Higgs masses, the observed M_{ZZ} distribution is dominated by experimental resolution effects and for example fitted as Gaussian with a standard deviation of 2–2.5 GeV (or similar bin sizes are used). The constraints on M_{ZZ} (binning) introduce an error of order 0.1%. Invariant masses above $2\,M_Z$, where large deviations from the Breit-Wigner shape occur, are excluded by the experimental procedure. Higgs-continuum interference effects are negligible.

Light Higgs: Analysis with selection cuts

$gg \to H \to ZZ \to \ell\bar{\ell}\ell\bar{\ell}$ and $\ell\bar{\ell}\ell'\bar{\ell}'$ at $M_H = 125$ GeV

	$gg\ (\to H) \to ZZ \to 4\ell$ and $2\ell\,2\ell'$						
	σ [fb], pp, $\sqrt{s} = 8$ TeV, $M_H = 125$ GeV				ZWA	interference	
mode	H_{ZWA}	H_{offshell}	cont	$\lvert H_{\text{ofs}}\text{+cont}\rvert^2$	R_0	R_1	R_2
$\ell\bar{\ell}\,\ell\bar{\ell}$	0.0748(2)	0.0747(2)	0.000437(3)	0.0747(6)	1.002(3)	0.994(8)	0.994(8)
$\ell\bar{\ell}\,\ell'\bar{\ell}'$	0.1395(2)	0.1393(2)	0.000583(2)	0.1400(3)	1.002(2)	1.001(2)	1.001(2)

Cross sections for $gg\ (\to\ H)\ \to ZZ\ \to \ell\bar{\ell}\ell\bar{\ell}$ and $\ell\bar{\ell}\ell'\bar{\ell}'$ in pp collisions at $\sqrt{s}\ =\ 8$ TeV for $M_H\ =\ 125$ GeV and $\Gamma_H\ =\ 0.004434$ GeV calculated at LO with gg2VV. The zero-width approximation (ZWA) and off-shell Higgs cross sections, the continuum cross section and the sum of off-shell Higgs and continuum cross sections including interference are given. The accuracy of the ZWA and the impact of off-shell effects are assessed with $R_0\ =\ \sigma_{H,\text{ZWA}}/\sigma_{H,\text{offshell}}$. Interference effects are illustrated through $R_1\ =\ \sigma(|\mathcal{M}_H + \mathcal{M}_{\text{cont}}|^2)/\sigma(|\mathcal{M}_H|^2 + |\mathcal{M}_{\text{cont}}|^2)$ and $R_2 = \sigma(|\mathcal{M}_H|^2 + 2\,\text{Re}(\mathcal{M}_H\mathcal{M}^*_{\text{cont}}))/\sigma(|\mathcal{M}_H|^2)$. γ^* contributions are included in $\mathcal{M}_{\text{cont}}$. Applied cuts: $\boldsymbol{|M_{ZZ} - M_H| < 1}$ **GeV**, $p_{T\ell} > 5$ GeV, $|\eta_\ell| < 2.5$, $\Delta R_{\ell\ell} > 0.1$, 76 GeV $< M_{\ell\bar{\ell},12} < 106$ GeV and 15 GeV $< M_{\ell\bar{\ell},34} < 115$ GeV, $M_{\ell\bar{\ell}} > 4$ GeV. The invariant mass of the same-flavour, opposite-sign lepton pair closest to M_Z is denoted by $M_{\ell\bar{\ell},12}$. $M_{\ell\bar{\ell},34}$ denotes the invariant mass of the remaining lepton pair. Cross sections are given for a single lepton flavour combination. No flavour summation is carried out for charged leptons or neutrinos. The integration error is given in brackets.

Light Higgs: Analysis with selection cuts

$gg \to H \to W^-W^+ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ at $M_H = 125$ GeV

	$gg\ (\to H) \to W^-W^+ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$						
	σ [fb], pp, $\sqrt{s} = 8$ TeV, $M_H = 125$ GeV				ZWA	interference	
selection cuts	H_{ZWA}	H_{offshell}	cont	$\lvert H_{\text{ofs}}+\text{cont}\rvert^2$	R_0	R_1	R_2
standard cuts	2.707(3)	3.225(3)	10.493(5)	12.241(8)	0.839(2)	0.8923(7)	0.542(3)
Higgs search cuts	1.950(1)	1.980(1)	2.705(2)	4.497(3)	0.9850(7)	0.9599(7)	0.905(2)
$0.75 M_H < M_{T1} < M_H$	1.7726(9)	1.779(1)	0.6443(9)	2.383(2)	0.9966(8)	0.983(1)	0.977(2)
80 GeV $< M_{T2} < M_H$	1.7843(9)	1.794(1)	0.955(1)	2.687(3)	0.9944(8)	0.977(1)	0.965(2)

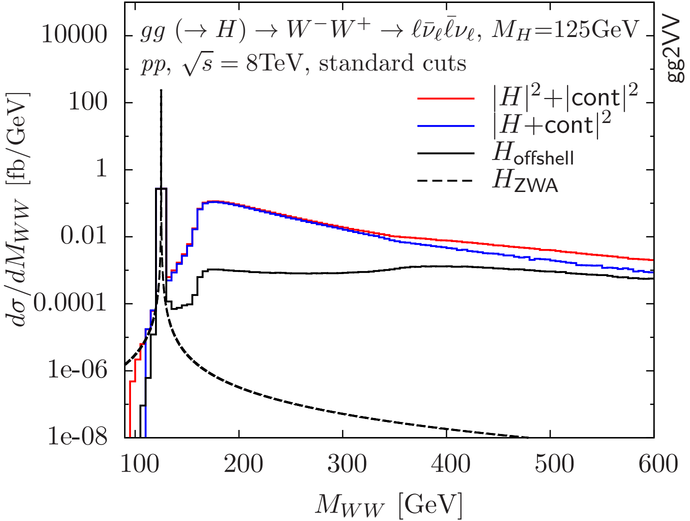
Cross sections for $gg\ (\to H) \to W^-W^+ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ for $M_H = 125$ GeV with standard cuts, Higgs search cuts and additional transverse mass cut (either on M_{T1} or M_{T2}). Standard cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, $\not{p}_T > 30$ GeV, $M_{\ell\ell} > 12$ GeV. Higgs search cuts: standard cuts and $M_{\ell\ell} <$ 50 GeV, $\Delta\phi_{\ell\ell} < 1.8$.

cannot reconstruct M_{H^*}: use transverse mass observable M_T as proxy:

ATLAS: $M_{T1} = \sqrt{(M_{T,\ell\ell} + \not{p}_T)^2 - (\mathbf{p}_{T,\ell\ell} + \not{\mathbf{p}}_T)^2}$ with $M_{T,\ell\ell} = \sqrt{p_{T,\ell\ell}^2 + M_{\ell\ell}^2}$

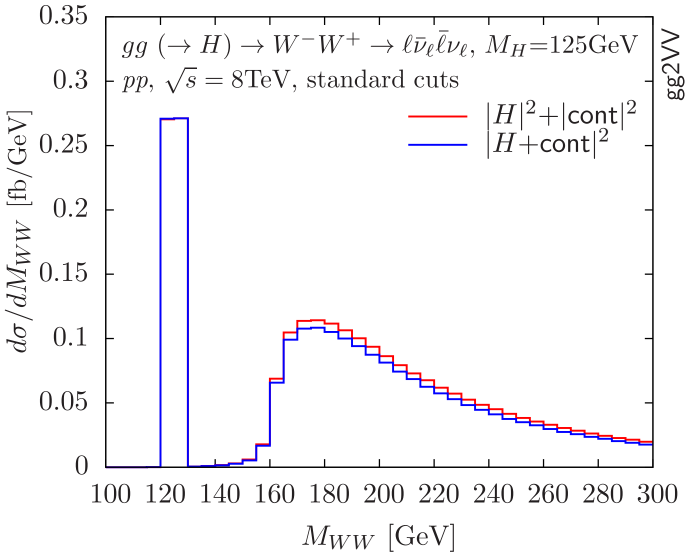
CMS: $M_{T2} = \sqrt{2\, p_{T,\ell\ell}\, \not{p}_T (1 - \cos\Delta\phi_{\ell\ell,\text{miss}})}$ with $\Delta\phi_{\ell\ell,\text{miss}} = \angle(\mathbf{p}_{T,\ell\ell};\ \not{\mathbf{p}}_T)$

Light Higgs: Analysis with selection cuts



Standard cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, $\not{p}_T > 30$ GeV, $M_{\ell\ell} > 12$ GeV

Light Higgs: Analysis with selection cuts



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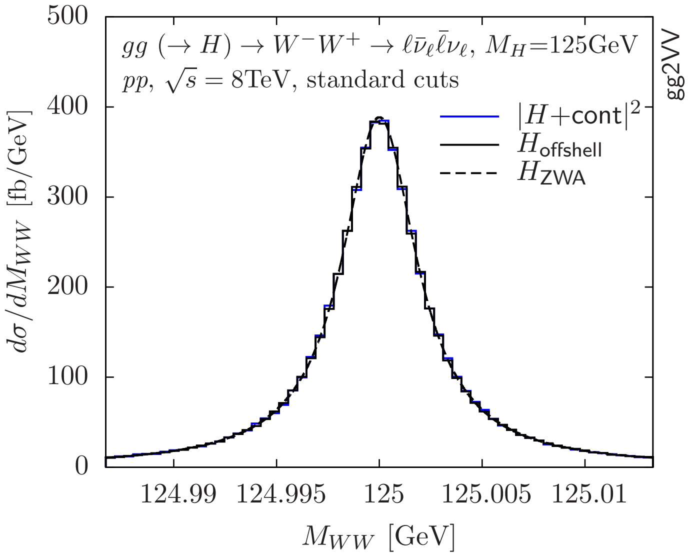

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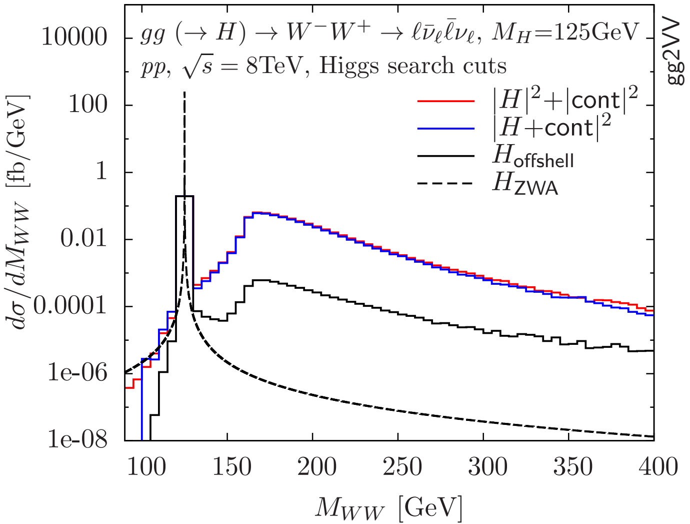
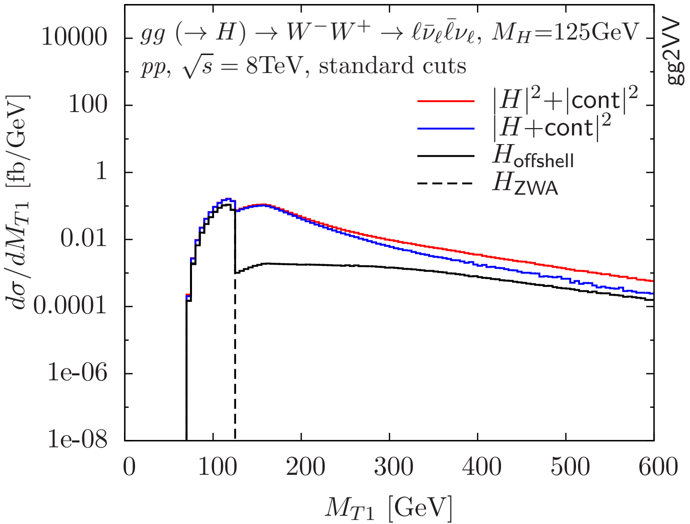
Light Higgs: Analysis with selection cuts



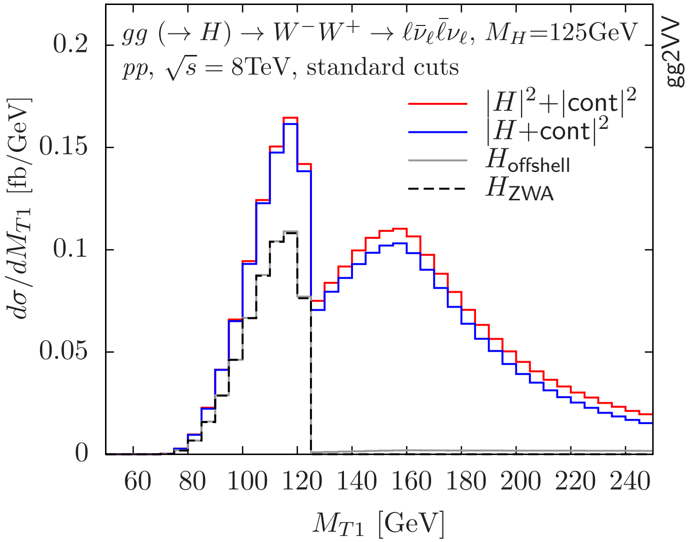
Higgs search cuts: $p_{T\ell} > 20\,\text{GeV}$, $|\eta_\ell| < 2.5$, $\not{p}_T > 30\,\text{GeV}$, $12\,\text{GeV} < M_{\ell\ell} < 50\,\text{GeV}$, $\Delta\phi_{\ell\ell} < 1.8$.

Light Higgs: Analysis with selection cuts



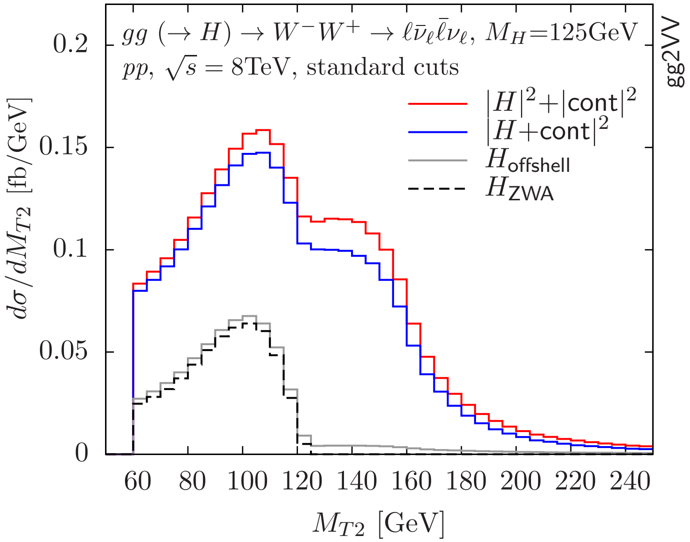
Standard cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, $\not{p}_T > 30$ GeV, $M_{\ell\ell} > 12$ GeV

Light Higgs: Analysis with selection cuts



Standard cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, $\not{p}_T > 30$ GeV, $M_{\ell\ell} > 12$ GeV

Light Higgs: Analysis with selection cuts



Standard cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, $\not{p}_T > 30$ GeV, $M_{\ell\ell} > 12$ GeV

Light Higgs: Analysis with selection cuts

$gg \to H \to ZZ \to \ell\bar{\ell}\nu_\ell\bar{\nu}_\ell$ at $M_H = 200$ GeV

- $M_H > 2\,M_Z$ (Higgs resonance in region with large continuum background)
- $\Gamma_H/M_H = 0.7\%$
- M_{T3}, unlike M_{T1} and M_{T2}, does not have a kinematic edge at M_{H^*}
- significant constructive signal-background interference occurs

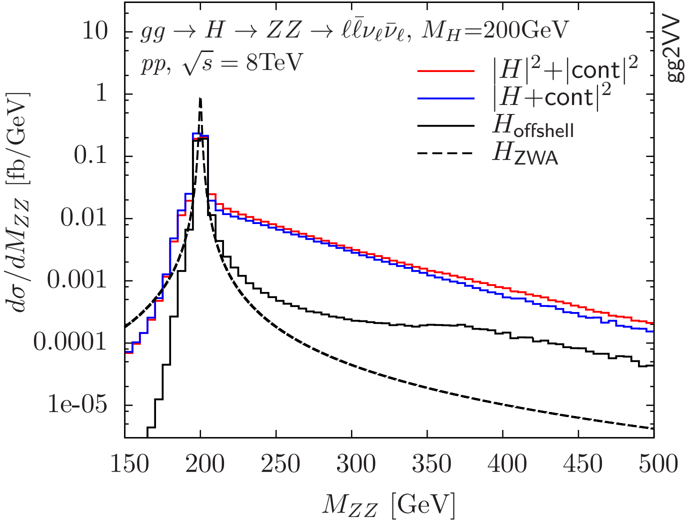
$gg\ (\to H) \to ZZ \to \ell\bar{\ell}\nu_\ell\bar{\nu}_\ell$						
σ [fb], pp, $\sqrt{s} = 8$ TeV, $M_H = 200$ GeV				ZWA	interference	
H_{ZWA}	H_{offshell}	cont	$\lvert H_{\text{ofs}}\text{+cont}\rvert^2$	R_0	R_1	R_2
2.0357(8)	2.0608(9)	1.1888(6)	3.380(2)	0.9878(6)	1.0400(7)	1.063(1)

Cross sections for $gg\ (\to H) \to ZZ \to \ell\bar{\ell}\nu_\ell\bar{\nu}_\ell$ for $M_H = 200$ GeV and $\Gamma_H = 1.428$ GeV. Applied cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, 76 GeV $< M_{\ell\ell} < 106$ GeV, $\not{p}_T > 10$ GeV, $\Delta\phi_{\ell\ell} > 1$.

CMS: $M_{T3} = \sqrt{\left(M_{T,\ell\ell} + \not{M}_T\right)^2 - (\mathbf{p}_{T,\ell\ell} + \not{\mathbf{p}}_T)^2}$ with $\not{M}_T = \sqrt{\not{p}_T^2 + M_{\ell\ell}^2}$

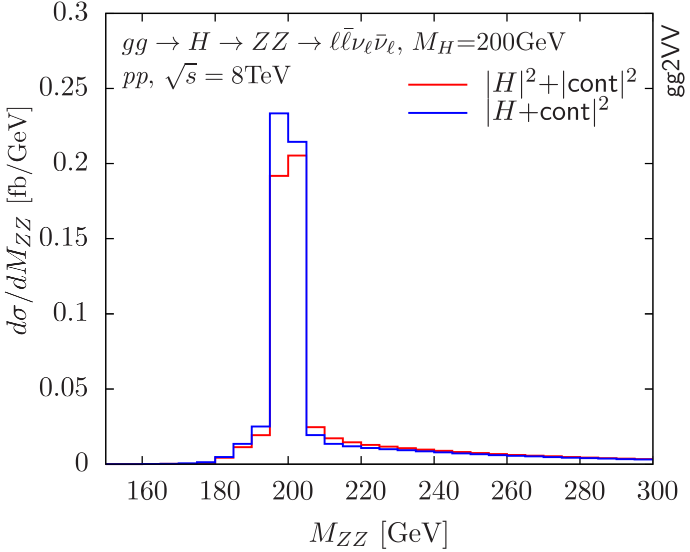
ATLAS uses M_{T3} with $M_{\ell\ell} \to M_Z$

Light Higgs: Analysis with selection cuts



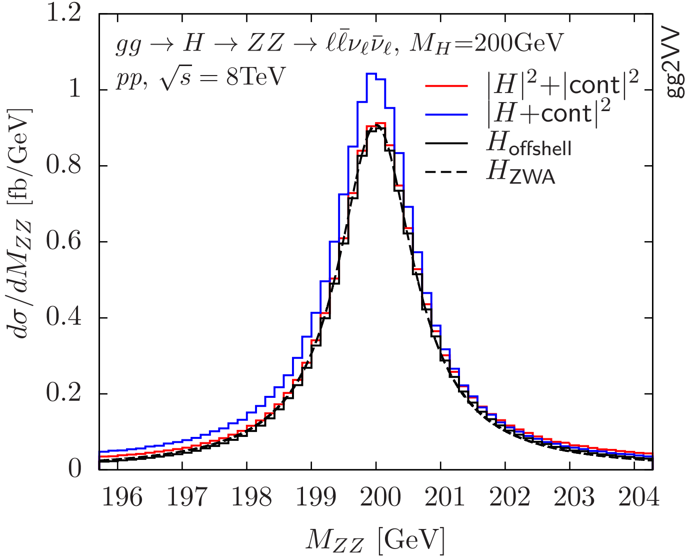
Applied cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, 76 GeV $< M_{\ell\ell} < 106$ GeV, $\not{p}_T > 10$ GeV, $\Delta\phi_{\ell\ell} > 1$

Light Higgs: Analysis with selection cuts



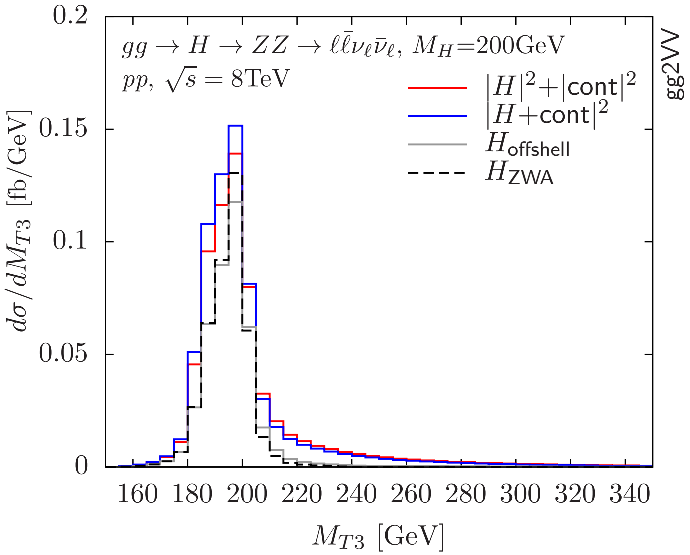
Applied cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, 76 GeV $< M_{\ell\ell} < 106$ GeV, $\not{p}_T > 10$ GeV, $\Delta\phi_{\ell\ell} > 1$

Light Higgs: Analysis with selection cuts



Applied cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, 76 GeV $< M_{\ell\ell} <$ 106 GeV, $\not{p}_T > 10$ GeV, $\Delta\phi_{\ell\ell} > 1$

Light Higgs: Analysis with selection cuts



Applied cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, 76 GeV $< M_{\ell\ell} < 106$ GeV, $\not{p}_T > 10$ GeV, $\Delta\phi_{\ell\ell} > 1$

Light Higgs: Analysis with selection cuts

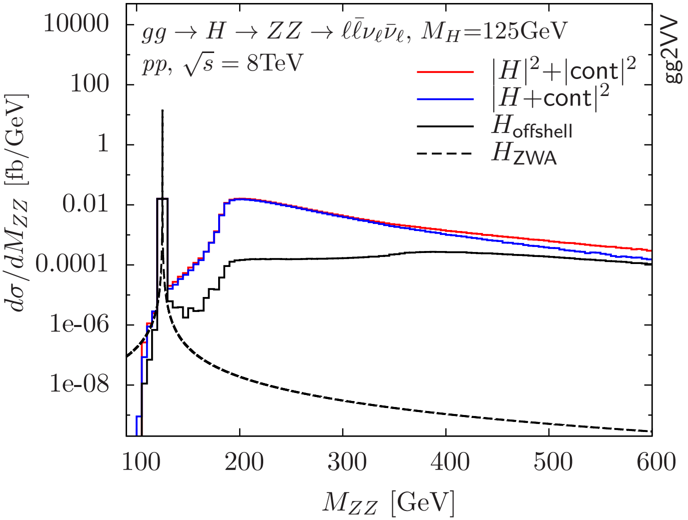
$gg \to H \to ZZ \to \ell\bar{\ell}\nu_\ell\bar{\nu}_\ell$ at $M_H = 125$ GeV

- no experimental studies of this channel at $M_H = 125$ GeV yet
- off-shell enhancement of tail is stronger for ZZ than WW
- $M_{ZZ} > 180$ GeV $= M_H + 12000\Gamma_H$: 37% of off-shell signal ($\not{p}_T$ cut dependent)
- ZWA inappropriate, large interference
- significant mitigation if $M_{T1} < M_H$ cut is applied

	$gg\ (\to H) \to ZZ \to \ell\bar{\ell}\nu_\ell\bar{\nu}_\ell$						
	σ [fb], pp, $\sqrt{s} = 8$ TeV, $M_H = 125$ GeV				ZWA	interference	
M_T cut	H_{ZWA}	H_{offshell}	cont	$\lvert H_{\text{ofs}}\text{+cont}\rvert^2$	R_0	R_1	R_2
none	0.1593(2)	0.2571(2)	1.5631(7)	1.6376(9)	0.6196(7)	0.8997(6)	0.290(5)
$M_{T1} < M_H$	0.1593(2)	0.1625(2)	0.4197(5)	0.5663(6)	0.980(2)	0.973(2)	0.902(5)

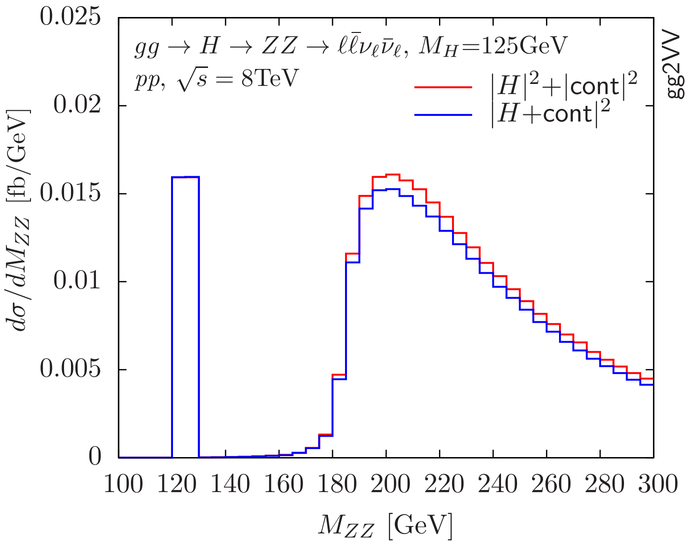
Cross sections for $gg\ (\to H) \to ZZ \to \ell\bar{\ell}\nu_\ell\bar{\nu}_\ell$ for $M_H = 125$ GeV without and with transverse mass cut. Applied cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, 76 GeV $< M_{\ell\ell} < 106$ GeV, $\not{p}_T > 10$ GeV.

Light Higgs: Analysis with selection cuts



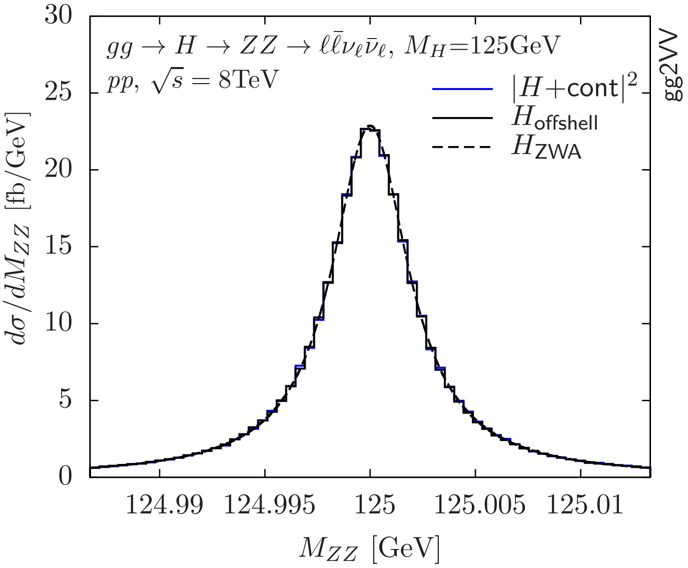
Applied cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, 76 GeV $< M_{\ell\ell} < 106$ GeV, $\not{p}_T > 10$ GeV

Light Higgs: Analysis with selection cuts



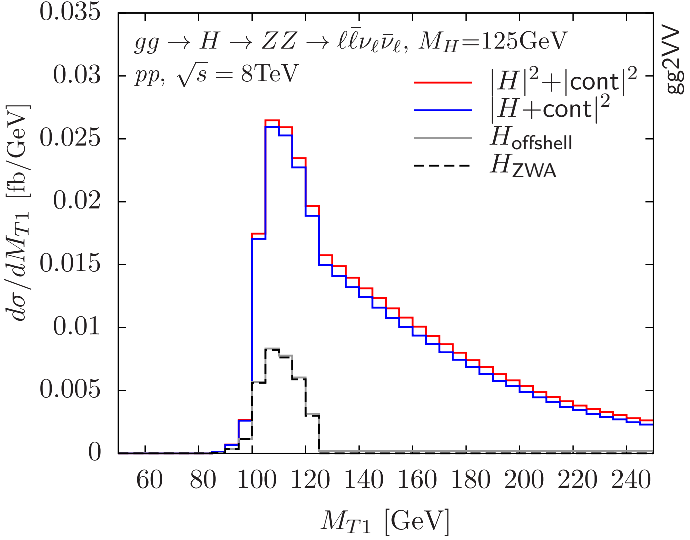
Applied cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, 76 GeV $< M_{\ell\ell} < 106$ GeV, $\not{p}_T > 10$ GeV

Light Higgs: Analysis with selection cuts



Applied cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, 76 GeV $< M_{\ell\ell} < 106$ GeV, $\not{p}_T > 10$ GeV

Light Higgs: Analysis with selection cuts



Applied cuts: $p_{T\ell} > 20\,\text{GeV}$, $|\eta_\ell| < 2.5$, $76\,\text{GeV} < M_{\ell\ell} < 106\,\text{GeV}$, $\not{p}_T > 10\,\text{GeV}$

Light Higgs analysis

$gg \to H \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ (same flavour) at $M_H = 125$ GeV

	$gg\ (\to H) \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$				
	σ [fb], pp, $\sqrt{s} = 8$ TeV, $M_H = 125$ GeV			interference	
selection cuts	H_{offshell}	cont	$\lvert H_{\text{ofs}}\text{+cont}\rvert^2$	R_1	R_2
standard cuts	3.225(4)	11.42(5)	12.95(8)	0.884(6)	0.47(3)
Higgs search cuts	1.919(3)	2.711(7)	4.438(8)	0.958(3)	0.900(6)
$+(0.75M_H < M_{T1} < M_H)$	1.736(2)	0.645(2)	2.335(4)	0.981(2)	0.974(3)

(details as on p. 16)

For comparison: **ratio** to different-flavour results (see p. 16):

	$gg\ (\to H) \to WW \to \ell\bar{\nu}_\ell\bar{\ell}'\nu_{\ell'}$				
	σ [fb], pp, $\sqrt{s} = 8$ TeV, $M_H = 125$ GeV			interference	
selection cuts	H_{offshell}	cont	$\lvert H_{\text{ofs}}\text{+cont}\rvert^2$	R_1	R_2
standard cuts	1.000(2)	1.088(5)	1.058(7)	0.991(7)	0.88(6)
Higgs search cuts	0.969(2)	1.002(3)	0.987(2)	0.998(3)	0.994(6)
$+(0.75M_H < M_{T1} < M_H)$	0.976(2)	1.001(3)	0.980(2)	0.997(3)	0.996(3)

$gg \to ZZ$: Comparison of gg2ZZ and MCFM

Contribution to LHC Higgs Cross Section Working Group Report 2

Specification

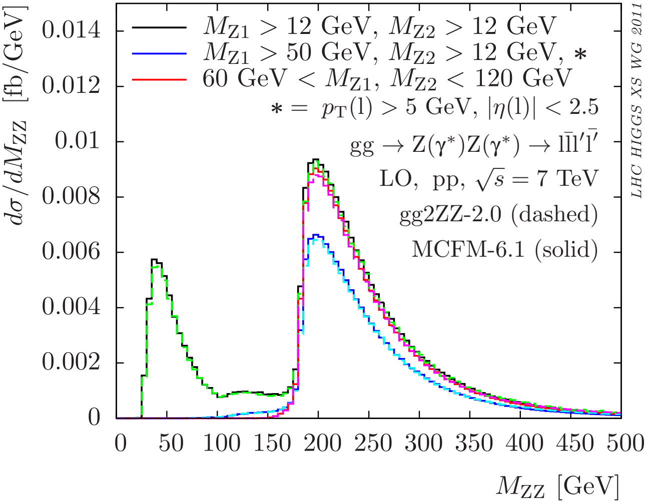
Parton-level cross sections and M_{ZZ} distributions for pp collisions at $\sqrt{s} = 7$ TeV are compared for three cut sets: $M_{Z1} > 12$ GeV, $M_{Z2} > 12$ GeV (cuts 1); $M_{Z1} > 50$ GeV, $M_{Z2} > 12$ GeV, $p_T(\ell) > 5$ GeV, $|\eta(\ell)| < 2.5$ (cuts 2); 60 GeV $< M_{Z1} <$ 120 GeV, 60 GeV $< M_{Z2} <$ 120 GeV (cuts 3). In addition, a $p_T(Z) > 0.05$ GeV cut is applied to prevent that numerical instabilities spoil the amplitude evaluation. This technical cut reduces the cross sections by at most 0.05%. Results are given for a single lepton flavour combination, e.g. $\ell = e^-, \ell' = \mu^-$. Lepton masses are neglected. The input parameter set of arXiv:1101.0593, App. A, is used. More specifically, $M_Z = 91.1876$ GeV, NLO $\Gamma_Z = 2.49595$ GeV, $M_W = 80.398$ GeV, $G_F = 1.16637 \cdot 10^{-5}$ GeV^{-2}, $M_b = 4.75$ GeV and $M_t = 172.5$ GeV. The weak mixing angle is given by $c_\text{w} = M_W/M_Z$, $s_\text{w}^2 = 1 - c_\text{w}^2$. The electromagnetic coupling is defined in the G_μ scheme as $\alpha = \sqrt{2} G_F M_W^2 s_\text{w}^2/\pi$. The renormalisation and factorisation scales are set to M_Z. The PDF set MSTW2008NNLO with 3-loop running for $\alpha_s(\mu^2)$ and $\alpha_s(M_Z^2) = 0.11707$ is used. The fixed-width prescription is used for Z propagators.

Comparison of integrated cross sections

	$\sigma(gg \to Z(\gamma^*)Z(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}')$ [fb], pp, $\sqrt{s} = 7$ TeV		
	gg2ZZ-2.0	MCFM-6.1	$\sigma_{\text{MCFM}}/\sigma_{\text{gg2ZZ}}$
cuts 1	1.157(2)	1.168(2)	1.010(2)
cuts 2	0.6317(4)	0.6293(4)	0.9962(8)
cuts 3	0.8328(3)	0.8343(3)	1.0019(5)

$gg \to ZZ$: Comparison of gg2ZZ and MCFM

Comparison of differential distributions



$gg \to ZZ$: Comparison of gg2ZZ and MCFM

Calculational differences

The MCFM calculation exploits that the top quark decouples in good approximation. The t contribution to the quark loop is therefore neglected. The b contribution is included in the massless limit. In gg2ZZ, the b and t contributions are included with finite masses.

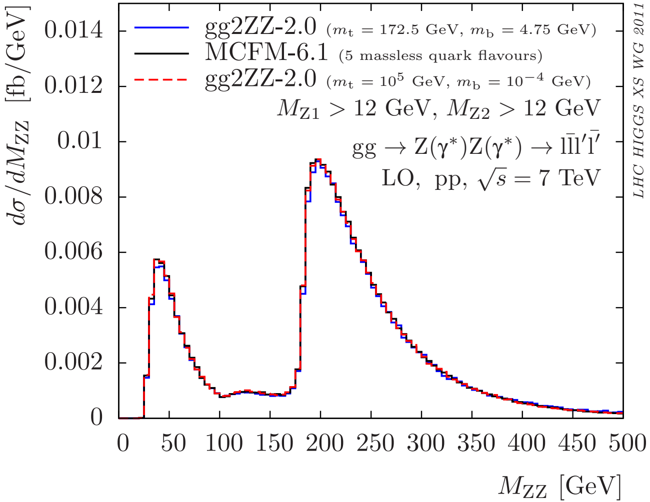
Amend specification: $M_t \to \infty, \;\; M_b \to 0$

Recomparison of integrated cross sections

cuts 1: $M_{Z1} > 12$ GeV, $M_{Z2} > 12$ GeV	σ [fb]	$\sigma_{\text{MCFM}}/\sigma_{\text{gg2ZZ}}$
gg2ZZ-2.0 ($M_t = 172.5$ GeV, $M_b = 4.75$ GeV)	1.157(2)	1.010(2)
MCFM-6.1 (5 massless quark flavours)	1.168(2)	—
gg2ZZ-2.0 ($M_t = 10^5$ GeV, $M_b = 10^{-4}$ GeV)	1.1677(8)	1.001(2)

$gg \to ZZ$: Comparison of gg2ZZ and MCFM

Recomparison of differential distributions



Interfacing with experimental tool chains

http://gg2VV.hepforge.org/

use gg2VV to generate weighted or unweighted events

for $|\mathcal{M}_\mathrm{H}|^2$, $|\mathcal{M}_\mathrm{cont}|^2$ and $|\mathcal{M}_\mathrm{H}+\mathcal{M}_\mathrm{cont}|^2$

Higgs amplitude: complex pole/Bar, OFFP schemes applied by default

in Les Houches standard format   Boos *et al.* (2001), Alwall *et al.* (2006)

$\rightarrow$ experimenters can investigate interference effects in their studies

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0.0238075 4.9e-05 1 661
</init>
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21 -1 0 0 502 501 -0 -0 -16.80868571 16.80868571 0. 0. 9.
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-15 1 1 2 0 0 0.66421985152 -6.3356495661 19.864846504 20.861298379 0. 0. 9.
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Signal-background interference for $M_H = 400$ GeV
$gg\,(\to H) \to W^-W^+ \to l\bar{\nu}_l \bar{l}'\nu_{l'}$ and $gg\,(\to H) \to ZZ \to l\bar{l}l'\bar{l}'$

Settings and cuts

$\mu_R = \mu_F = M_H/2 = 200$ GeV, $\Gamma_H = 29.16$ GeV (HDECAY)
MSTW2008LO (68% C.L.), other: LHC Higgs Cross Section WG, arXiv:1101.0593 [hep-ph], App. A (with NLO Γ_V and G_μ scheme)

$\boldsymbol{WW}$ **standard cuts**:

$p_{T\ell} > 20$ GeV , $|\eta_\ell| < 2.5$

$\not{p}_T > 30$ GeV , $M_{\ell\bar{\ell}'} > 12$ GeV

$\boldsymbol{WW}$ **Higgs search cuts** ($M_H = 400$ GeV): standard cuts and

$p_{T\ell\text{min}} > 25$ GeV , $p_{T\ell\text{max}} > 90$ GeV

$M_{\ell\bar{\ell}'} < 300$ GeV , $\Delta\phi_{\ell\bar{\ell}'} < 175°$

$\boldsymbol{ZZ}$ **standard cuts**:

$p_{T\ell} > 20$ GeV , $|\eta_\ell| < 2.5$

76 GeV $< M_{\ell\bar{\ell}}, M_{\ell'\bar{\ell}'} < 106$ GeV

$\boldsymbol{ZZ}$ **Higgs search cuts**: standard cuts and

$|M_{l\bar{l}l'\bar{l}'} - M_H| < \Gamma_H$

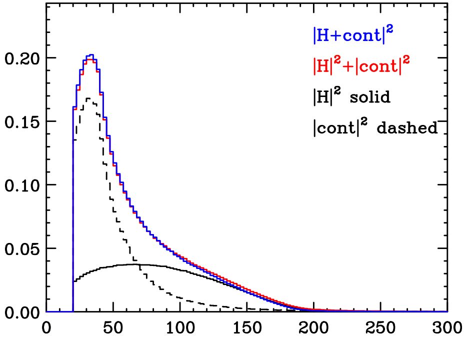
Signal-background interference for $M_H = 400$ GeV
Integrated results

		σ [fb], pp, $\sqrt{s} = 7$ TeV, $M_H = 400$ GeV			interference	
process	cuts	$\lvert\mathcal{M}_H\rvert^2$	$\lvert\mathcal{M}_{\text{cont}}\rvert^2$	$\lvert\mathcal{M}_H + \mathcal{M}_{\text{cont}}\rvert^2$	R_1	R_2
$gg\ (\to H) \to WW$	stand.	4.361(3)	6.351(4)	10.582(7)	0.9879(8)	0.970(2)
$gg\ (\to H) \to WW$	Higgs	2.502(2)	0.633(1)	3.007(3)	0.959(2)	0.949(2)
$gg\ (\to H) \to ZZ$	stand.	0.3654(4)	0.3450(4)	0.7012(8)	0.987(2)	0.975(3)
$gg\ (\to H) \to ZZ$	Higgs	0.2729(3)	0.01085(2)	0.2867(3)	1.010(2)	1.011(2)

		σ [fb], pp, $\sqrt{s} = 14$ TeV, $M_H = 400$ GeV			interference	
process	cuts	$\lvert\mathcal{M}_H\rvert^2$	$\lvert\mathcal{M}_{\text{cont}}\rvert^2$	$\lvert\mathcal{M}_H + \mathcal{M}_{\text{cont}}\rvert^2$	R_1	R_2
$gg\ (\to H) \to WW$	stand.	23.38(2)	26.47(2)	48.26(4)	0.9680(8)	0.932(2)
$gg\ (\to H) \to WW$	Higgs	13.54(2)	3.201(5)	15.74(2)	0.940(2)	0.926(2)
$gg\ (\to H) \to ZZ$	stand.	1.893(3)	1.417(2)	3.205(5)	0.969(2)	0.945(3)
$gg\ (\to H) \to ZZ$	Higgs	1.377(2)	0.0531(1)	1.445(2)	1.011(2)	1.011(3)

Signal-background interference for $M_H = 400$ GeV
Differential results

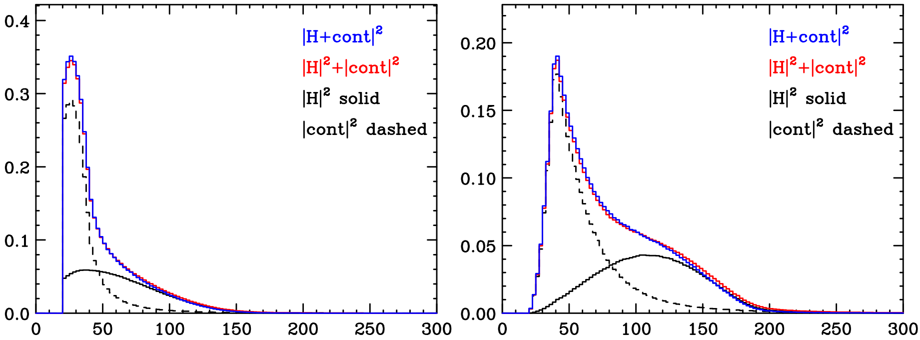
$gg\ (\to H) \to W^-W^+ \to l\bar{\nu}_l\bar{l'}\nu_{l'}$, LHC, 7 TeV, standard cuts



p_{Tl} [GeV] (left) and η_l (right) distributions [fb/[o]]

Signal-background interference for $M_H = 400$ GeV
Differential results

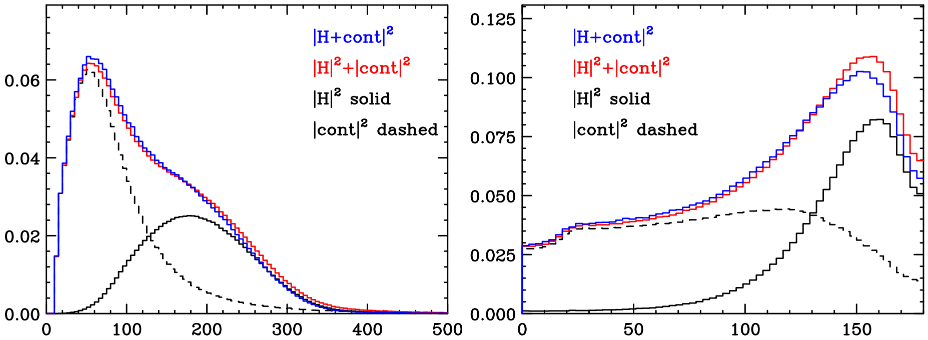
$gg\ (\to H) \to W^-W^+ \to l\bar{\nu}_l \bar{l'} \nu_{l'}$, LHC, 7 TeV, standard cuts



$p_{Tl,\text{min}}$ [GeV] (left) and $p_{Tl,\text{max}}$ [GeV] (right) distributions [fb/[o]]

Signal-background interference for $M_H = 400$ GeV
Differential results

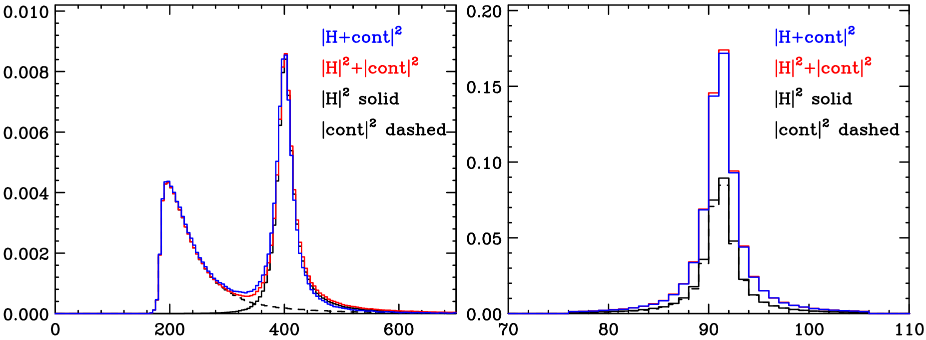
$gg\ (\to H) \to W^-W^+ \to l\bar{\nu}_l \bar{l}' \nu_{l'}$, LHC, 7 TeV, standard cuts



$M_{l\bar{l}'}$ [GeV] (left) and $\Delta\phi_{l\bar{l}'}$ [°] (right) distributions [fb/[o]]

Signal-background interference for $M_H = 400$ GeV
Differential results

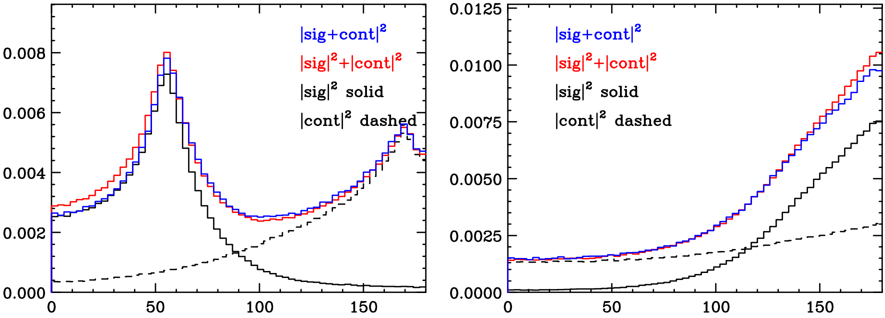
$gg\ (\to H) \to ZZ \to l\bar{l}l'\bar{l}'$, LHC, 7 TeV, standard cuts



$M_{l\bar{l}l'\bar{l}'}$ [GeV] (left) and $M_{l\bar{l}}$ [GeV] (right) distributions [fb/[o]]

Signal-background interference for $M_H = 400$ GeV
Differential results

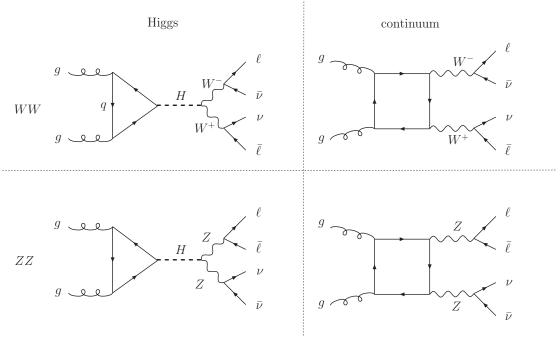
$gg\ (\to H) \to ZZ \to l\bar{l}l'\bar{l}'$, LHC, 7 TeV, standard cuts



$\Delta\phi_{\ell\bar{\ell}}$ (left) and $\Delta\phi_{\ell\ell'}$ (right) distributions [fb/[o]]

Heavy Higgs analysis

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



same flavour: all four contributions interfere (different flavour: WW only)

continuum WW/ZZ interference:

Nason and Rocket team studied continuum WW/ZZ interference in quark scattering (LO) $\longrightarrow$ negligible (arXiv:1107.5051)

$gg \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ with minimal cuts: negative interference of $\sim 6\%$ at 8 TeV

$$\sigma(WW + ZZ + \text{interference})/\sigma(WW + ZZ) = 0.935(5)$$

$gg \to H \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$: minimal cuts

	$gg\ (\to H) \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$				
	σ [fb], pp, $\sqrt{s} = 8$ TeV, $M_H = 600$ GeV			interference	
process	H_{offshell}	cont	$\lvert H_{\text{ofs}}\text{+cont}\rvert^2$	R_1	R_2
$gg\ (\to H) \to WW$	1.44(1)	12.29(3)	14.10(5)	1.027(4)	1.26(4)
$gg\ (\to H) \to ZZ$	0.261(2)	1.590(5)	1.896(6)	1.024(4)	1.17(3)
$gg\ (\to H) \to WW/ZZ$	1.69(2)	12.98(6)	15.00(8)	1.022(7)	1.19(6)

	$gg\ (\to H) \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$				
	σ [fb], pp, $\sqrt{s} = 8$ TeV, $M_H = 1000$ GeV			interference	
process	H_{offshell}	cont	$\lvert H_{\text{ofs}}\text{+cont}\rvert^2$	R_1	R_2
$gg\ (\to H) \to WW$	0.0772(5)	10.50(3)	10.72(3)	1.013(4)	2.8(5)
$gg\ (\to H) \to ZZ$	0.01426(9)	1.353(4)	1.387(4)	1.015(4)	2.4(4)
$gg\ (\to H) \to WW/ZZ$	0.0914(6)	11.02(6)	11.30(8)	1.017(9)	3(1)

minimal cuts: $M_{\ell\bar{\ell}} > 4$ GeV, $p_T(\ell\bar{\nu}_\ell) > 1$ GeV, $p_T(\ell\bar{\ell}) > 1$ GeV, parameters as above

$\mu_R = \mu_F = M_H/2$, CT10nnlo PDF, $\Gamma_H = 103.933\ (416.119)$ GeV for $M_H = 600\ (1000)$ GeV

$gg \to H \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$: $H \to ZZ$ search cuts

	$gg\ (\to H) \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$				
	σ [fb], pp, $\sqrt{s} = 8$ TeV, $M_H = 600$ GeV			interference	
process	H_{offshell}	cont	$\lvert H_{\text{ofs}}\text{+cont}\rvert^2$	R_1	R_2
$gg\ (\to H) \to ZZ$	0.2175(8)	0.0834(2)	0.3150(8)	1.047(4)	1.065(6)
$gg\ (\to H) \to WW/ZZ$	0.2220(8)	0.1020(2)	0.3406(8)	1.051(4)	1.075(6)

	$gg\ (\to H) \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$				
	σ [fb], pp, $\sqrt{s} = 8$ TeV, $M_H = 1000$ GeV			interference	
process	H_{offshell}	cont	$\lvert H_{\text{ofs}}\text{+cont}\rvert^2$	R_1	R_2
$gg\ (\to H) \to ZZ$	0.01265(5)	0.0687(2)	0.0927(2)	1.140(3)	1.90(2)
$gg\ (\to H) \to WW/ZZ$	0.01278(5)	0.0846(3)	0.1090(2)	1.119(3)	1.91(3)

$H \to ZZ$ search cuts: $|M_{\ell\bar{\ell}} - M_Z| < 15$ GeV, $\not{E}_T > 110$ GeV, $M_T > 325$ GeV

$M_T = \sqrt{(M_{T,\ell\ell} + \not{M}_T)^2 - (\mathbf{p}_{T,\ell\ell} + \not{\mathbf{p}}_T)^2}$ with $\not{M}_T = \sqrt{\not{p}_T^2 + M_{\ell\ell}^2}$, other as above

Outlook

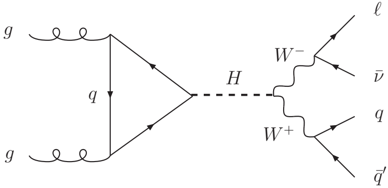
Interference effects for semileptonic final states

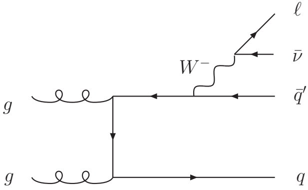
$$gg \to H \to W^-W^+ \to \ell\bar{\nu}_\ell q\bar{q}' \text{ (and c.c.)}$$

$$gg \to H \to ZZ \to \ell\bar{\ell}q\bar{q}$$

qualitative differences to $gg \to H \to 4$ leptons

interference with lower-order tree-level processes:





Summary

- $M_H \approx 125$ GeV: ZWA expected to be excellent ($\Gamma_H/M_H \approx 3 \cdot 10^{-5}$)
  But: M_H dependence of Higgs decay rates $\rightarrow$
  off-shell and interference effects are essential to reach 1% precision level
- $\mathcal{O}(5\text{–}10\%)$ corrections to inclusive $gg \rightarrow H \rightarrow VV$
  due to sizeable Higgs signal in region with invariant mass above $2M_V$
  even for $M_H = 125$ GeV (also for other Higgs production channels, e.g. VBF, VH, ...)
- $\mathcal{O}(100\%)$ corrections for very heavy Higgs signal
- experimental selection cuts (e.g. on M_T) allow to reduce/eliminate corrections
- Decay modes: 4ℓ is unproblematic, $2\ell 2\nu$ (diff. flavour): apply M_T cut
- heavy (BSM) Higgs search: $ZZ \rightarrow 2\ell 2\nu$: sizable effects with
  current experimental selections (need to be improved)
- $2\ell 2\nu$ (same-flavour): need to take into account WW/ZZ interference
  negative continuum $gg \rightarrow WW/ZZ$ interference of $\mathcal{O}(5\%)$
- gg2VV available (parton-level integrator and event generator)
- Higgs couplings extraction: need to go beyond ZWA
- other programs/event generators: make sure ZWA is not used explicitly/implicitly