# Interference effects from SM processes ($WW/ZZ$) to Higgs production/decay

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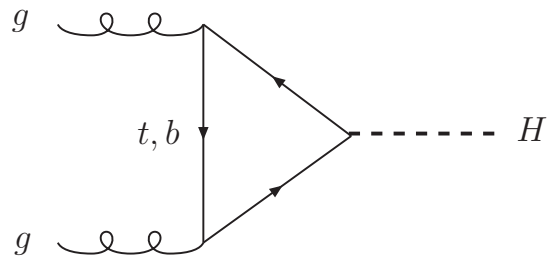
# Outline

- Introduction
- Light Higgs
- Heavy Higgs
- Outlook
- Summary

# 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)

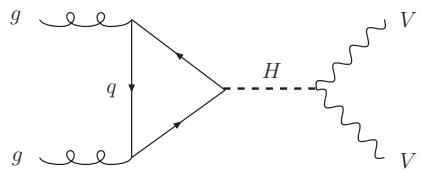
leading soft contributions @ NNNLO Moch, Vogt (2005); Laenen, Magnea (2006); Idilbi, Ji, Ma, Yuan (2006); Ravindran (2006)

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)

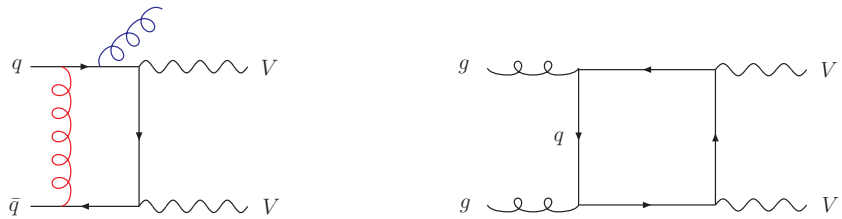
Recent updates de Florian, Grazzini (2009); Baglio, Djouadi (2010, 2011); Baglio, Djouadi, Ferrag, Godbole (2011); Catani, Grazzini (2011); Spira (HIGLU update); de Florian, Ferrera, Grazzini, Tommasini (2011, 2012) (HRes); LHCHXS2 (2012); Anastasiou, Buehler, Herzog, Lazopoulos (2012) (ihixs); de Florian,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

Higgs-continuum $VV$ 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; $\gamma\gamma$: Dixon, Siu (2003); Martin (2012)

# Light Higgs analysis

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

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

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

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

# Light Higgs analysis

## Relative measures for interference effect

$S + B$-inspired measure:

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

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

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

## Relative measure for off-shell effect (accuracy of ZWA)

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

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

## 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.

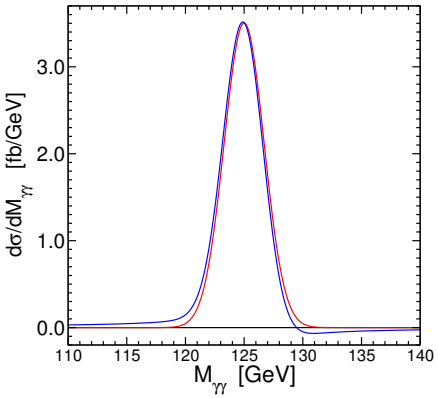
# $gg \to H \to ZZ \to \ell\bar{\ell}\ell\bar{\ell}$ and $\ell\bar{\ell}\ell'\bar{\ell}'$ at $M_H = 125\,\text{GeV}$

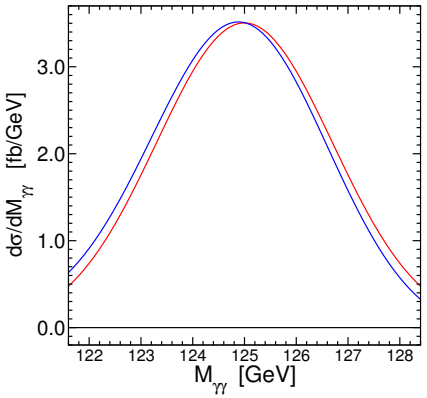
| | $gg\,(\to H) \to ZZ \to 4\ell$ and $2\ell\,2\ell'$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | $\sigma$ [fb], $pp$, $\sqrt{s} = 8\,\text{TeV}$, $M_H = 125\,\text{GeV}$ | | | | ZWA | interference | |
| mode | $H_{\text{ZWA}}$ | $H_{\text{offshell}}$ | cont | $\lvert H_{\text{ofs}}+\text{cont}\rvert^2$ | $R_0$ | $R_1$ | $R_2$ |
| $\ell\bar{\ell}\,\ell\bar{\ell}$ | 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 $\sqrt{s} = 8\,\text{TeV}$ for $M_H = 125\,\text{GeV}$ and $\Gamma_H = 0.004434\,\text{GeV}$ 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 $R_2 = \sigma(|\mathcal{M}_H|^2 + 2\,\text{Re}(\mathcal{M}_H\mathcal{M}^*_{\text{cont}}))/\sigma(|\mathcal{M}_H|^2)$. $\gamma^*$ contributions are included in $\mathcal{M}_{\text{cont}}$. Applied cuts: $\boxed{|M_{ZZ} - M_H| < 1\,\text{GeV}}$, $p_{T\ell} > 5\,\text{GeV}$, $|\eta_\ell| < 2.5$, $\Delta R_{\ell\ell} > 0.1$, $76\,\text{GeV} < M_{\ell\bar{\ell},12} < 106\,\text{GeV}$ and $15\,\text{GeV} < M_{\ell\bar{\ell},34} < 115\,\text{GeV}$, $M_{\ell\bar{\ell}} > 4\,\text{GeV}$. 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.

# Higgs invariant mass peak shift due to interference

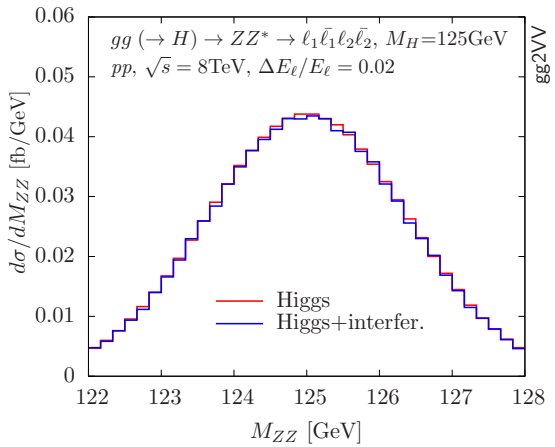
$gg \to H \to \gamma\gamma$ at $M_H = 125\,\text{GeV}$ (S.P. Martin, arXiv:1208.1533)




$M_{\gamma\gamma}$ resolution: Gaussian ($\sigma_M = 1.7$ GeV), $H \to \gamma\gamma$ peak shift: $\mathcal{O}(-150$ MeV)

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




$\to$ $H \to ZZ^*$ peak shift is tiny (compared to bin width of 167 MeV)

## Light Higgs analysis

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

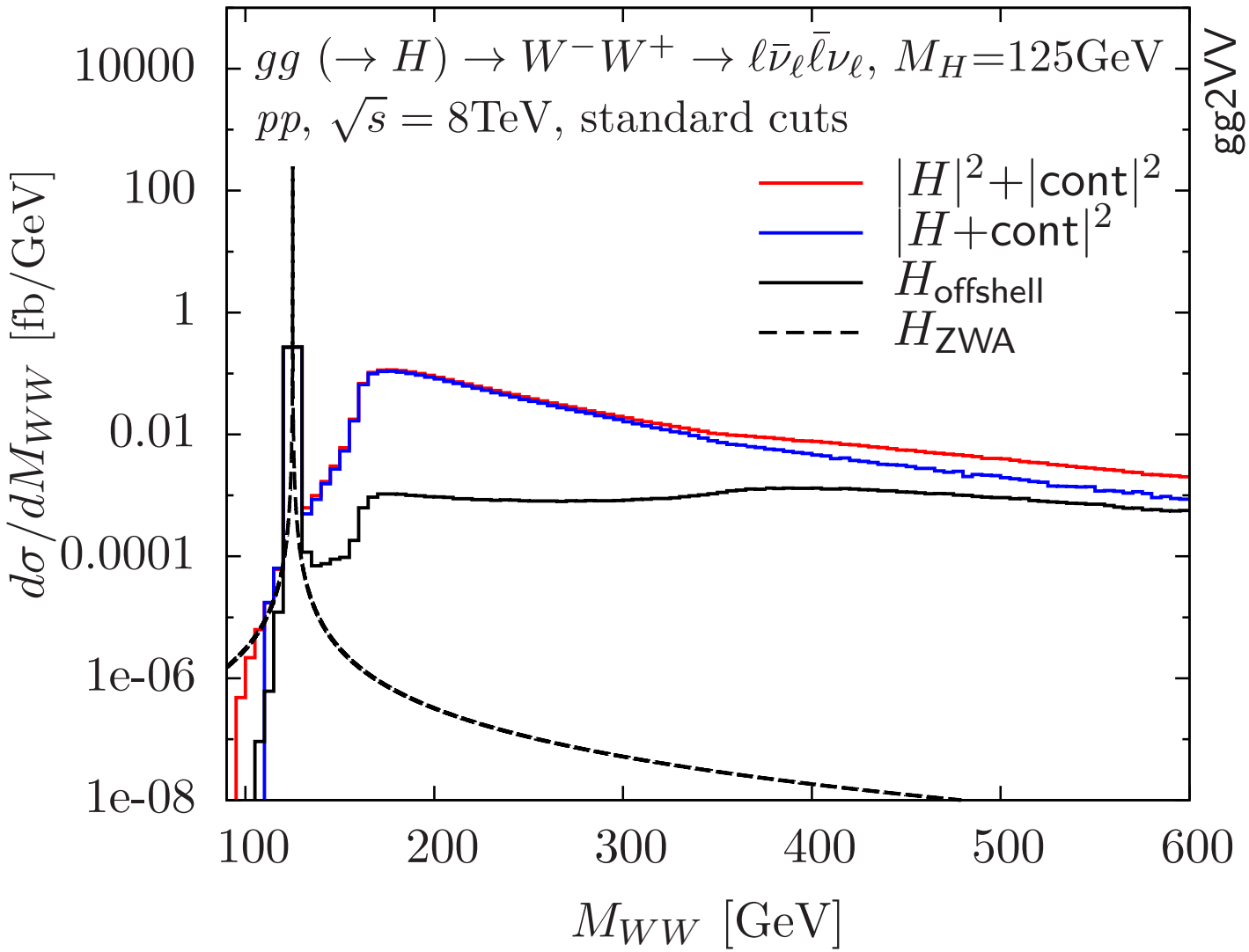
| | $gg\,(\to H) \to W^-W^+ \to \ell\bar{\nu}_\ell\bar{\ell}'\nu_{\ell'}$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | $\sigma$ [fb], $pp$, $\sqrt{s} = 8\,\text{TeV}$, $M_H = 125\,\text{GeV}$ | | | | ZWA | interference | |
| selection cuts | $H_{\text{ZWA}}$ | $H_{\text{offshell}}$ | cont | $\lvert H_{\text{ofs+cont}}\rvert^2$ | $R_0$ | $R_1$ | $R_2$ |
| 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) |
| $+(0.75M_H < M_{T1} < M_H)$ | 1.7726(9) | 1.779(1) | 0.6443(9) | 2.383(2) | 0.9966(8) | 0.983(1) | 0.977(2) |
| $+(80\ \text{GeV} < M_{T2} < M_H)$ | 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 $M_H = 125\,\text{GeV}$ with standard cuts, Higgs search cuts and additional transverse mass cut (either on $M_{T1}$ or $M_{T2}$). Standard cuts: $p_{T\ell} > 20\,\text{GeV}$, $|\eta_\ell| < 2.5$, $\not{p}_T > 30\,\text{GeV}$, $M_{\ell\ell} > 12\,\text{GeV}$. Higgs search cuts: standard cuts and $M_{\ell\ell} < 50\,\text{GeV}$, $\Delta\phi_{\ell\ell} < 1.8$.

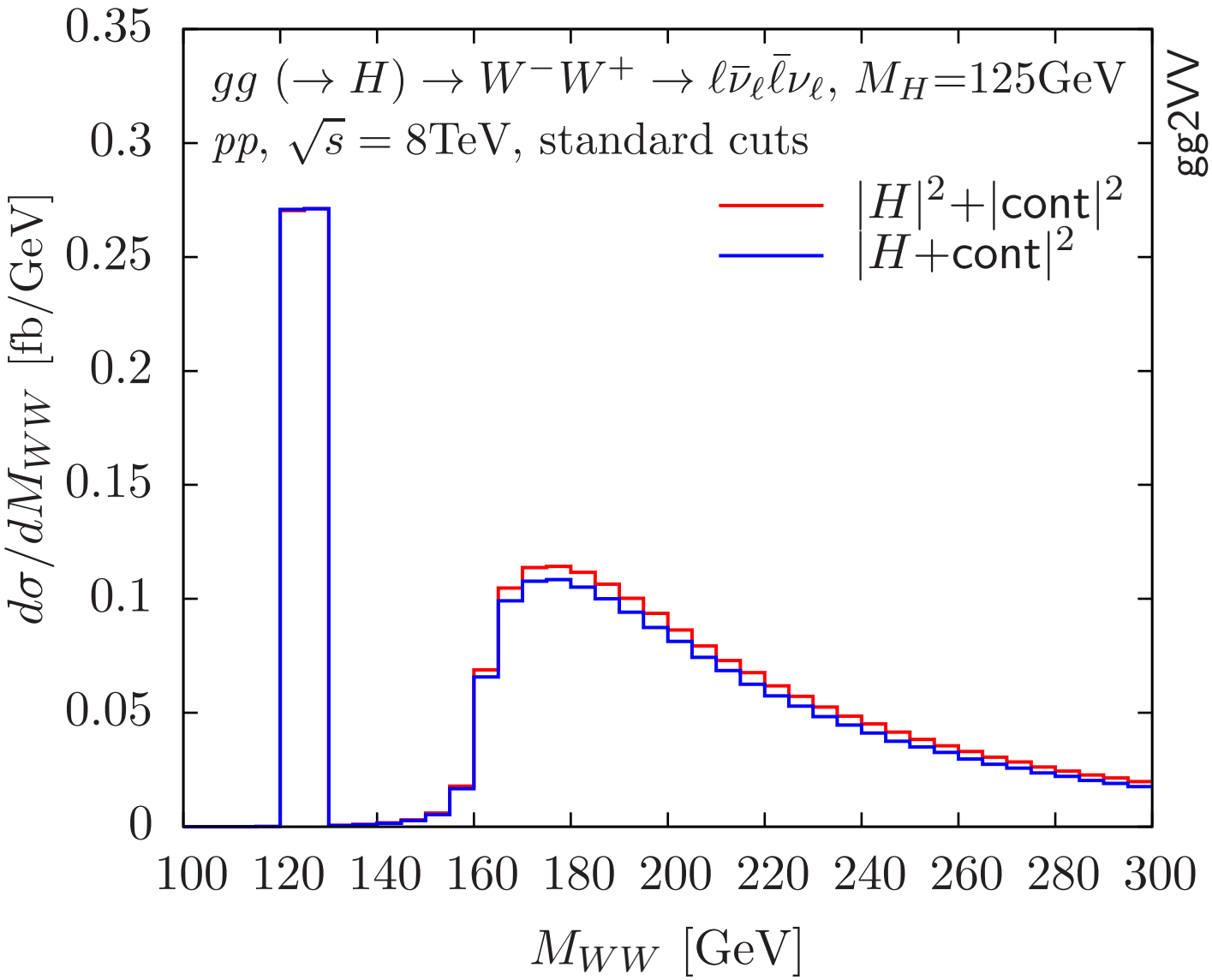
cannot reconstruct $M_{H^*}$: use transverse mass observable $M_T$ as proxy:

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

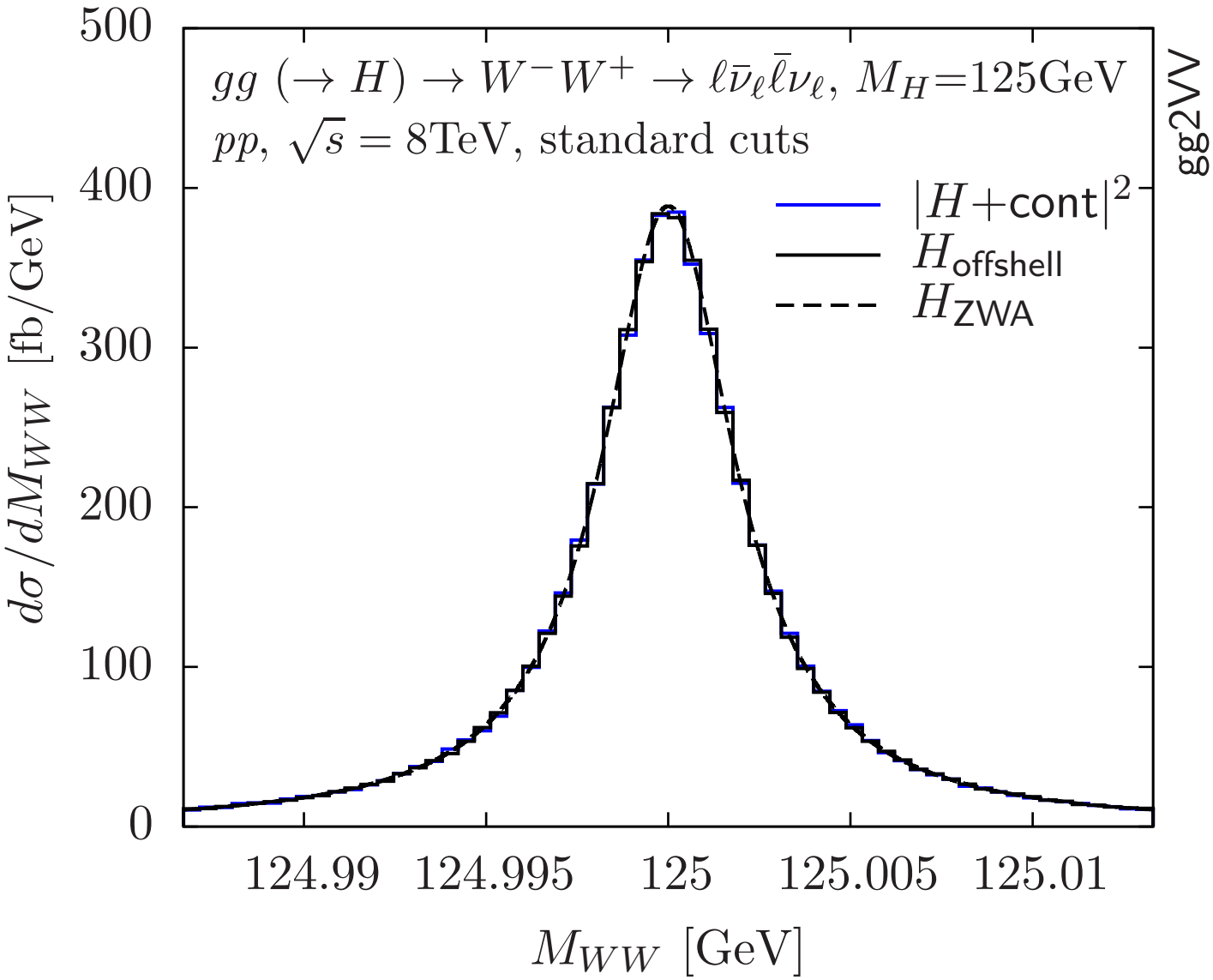
CMS: $M_{T2} = \sqrt{2\,p_{T,\ell\ell}\,\not{p}_T(1 - \cos\Delta\phi_{\ell\ell,\text{miss}})}$ with $\Delta\phi_{\ell\ell,\text{miss}} = \angle(\mathbf{p}_{T,\ell\ell};\ \not{\mathbf{p}}_T)$



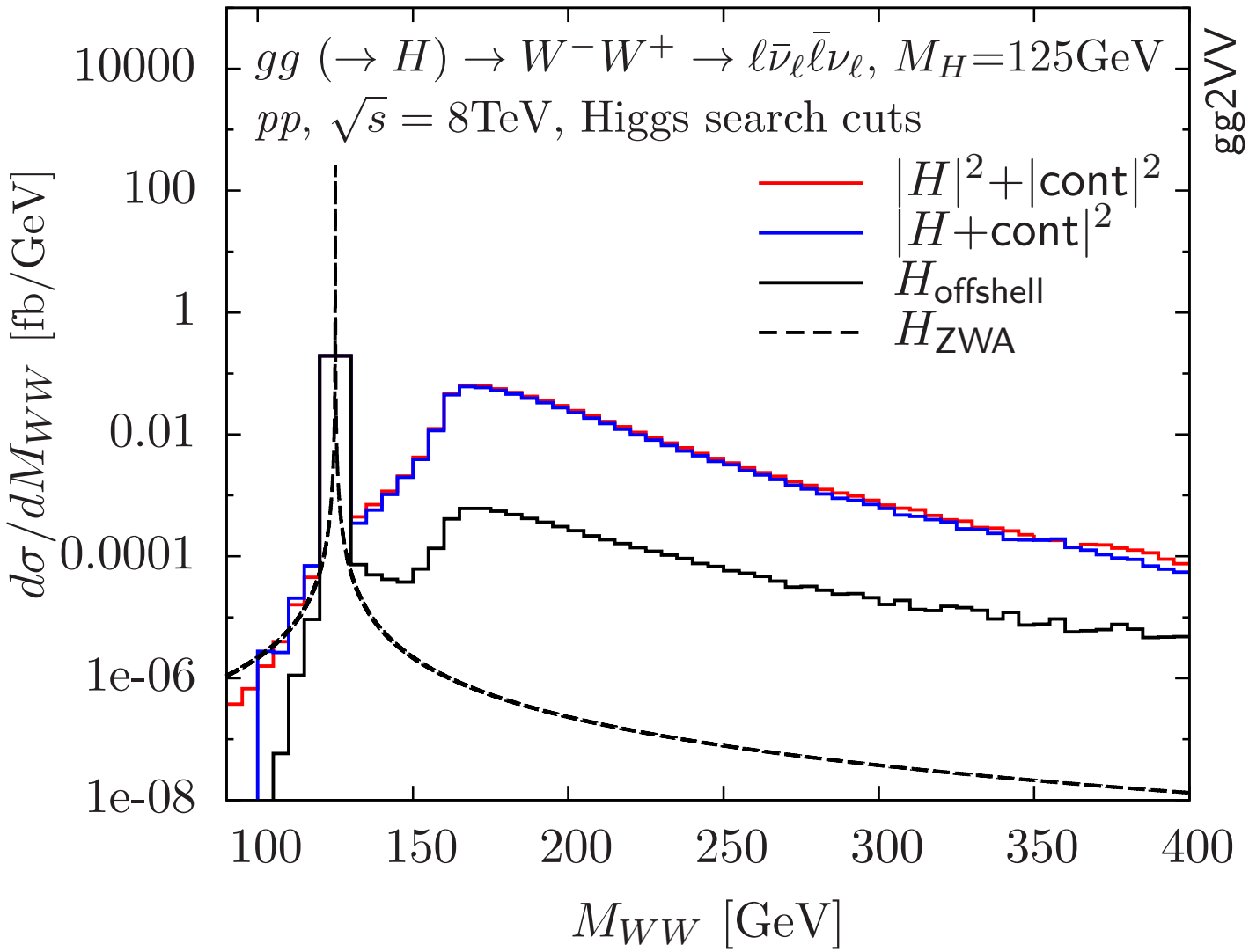

Standard cuts: $p_{T\ell} > 20\,\text{GeV}$, $|\eta_\ell| < 2.5$, $\not{p}_T > 30\,\text{GeV}$, $M_{\ell\ell} > 12\,\text{GeV}$



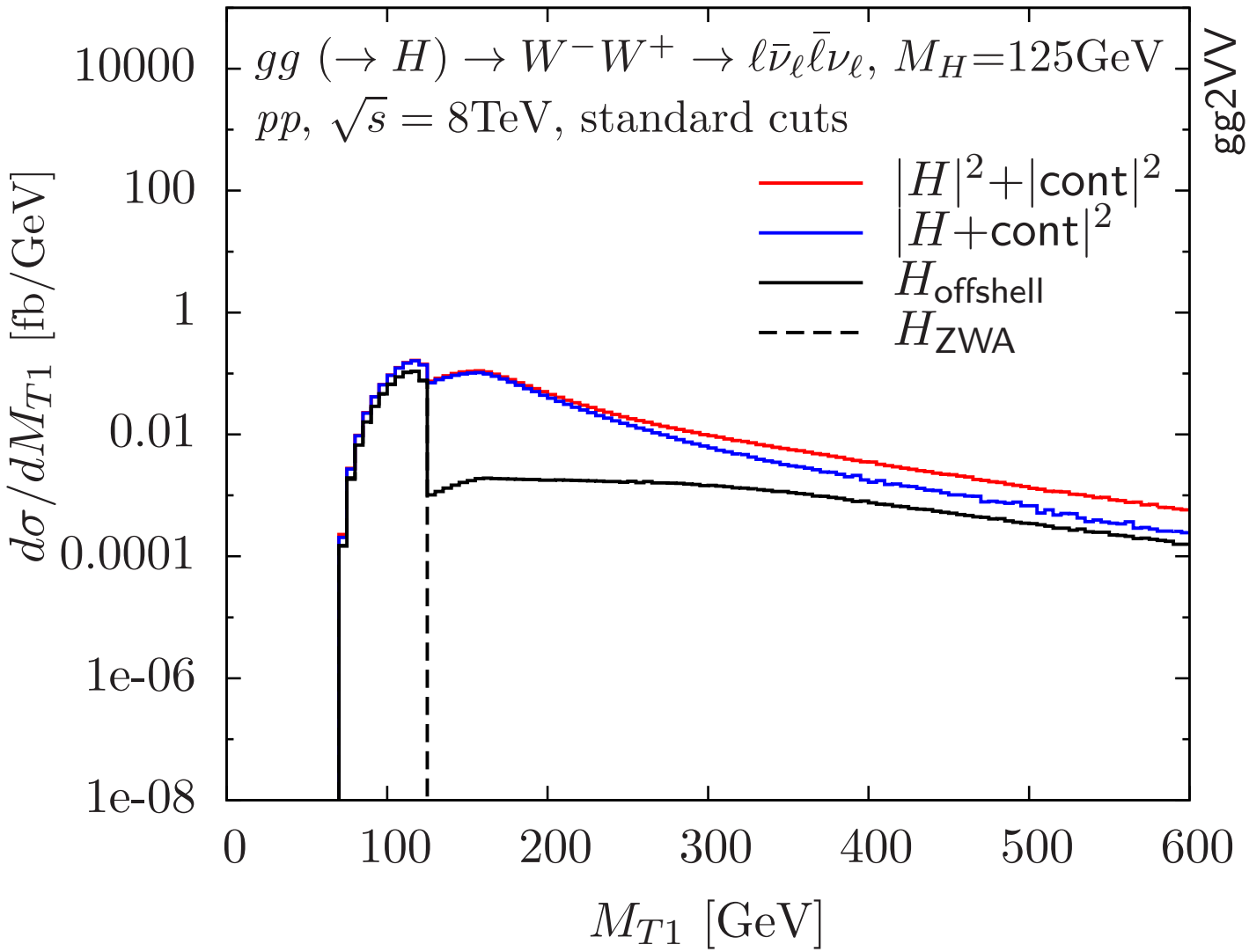

Standard cuts: $p_{T\ell} > 20\,\text{GeV}$, $|\eta_\ell| < 2.5$, $\not{p}_T > 30\,\text{GeV}$, $M_{\ell\ell} > 12\,\text{GeV}$



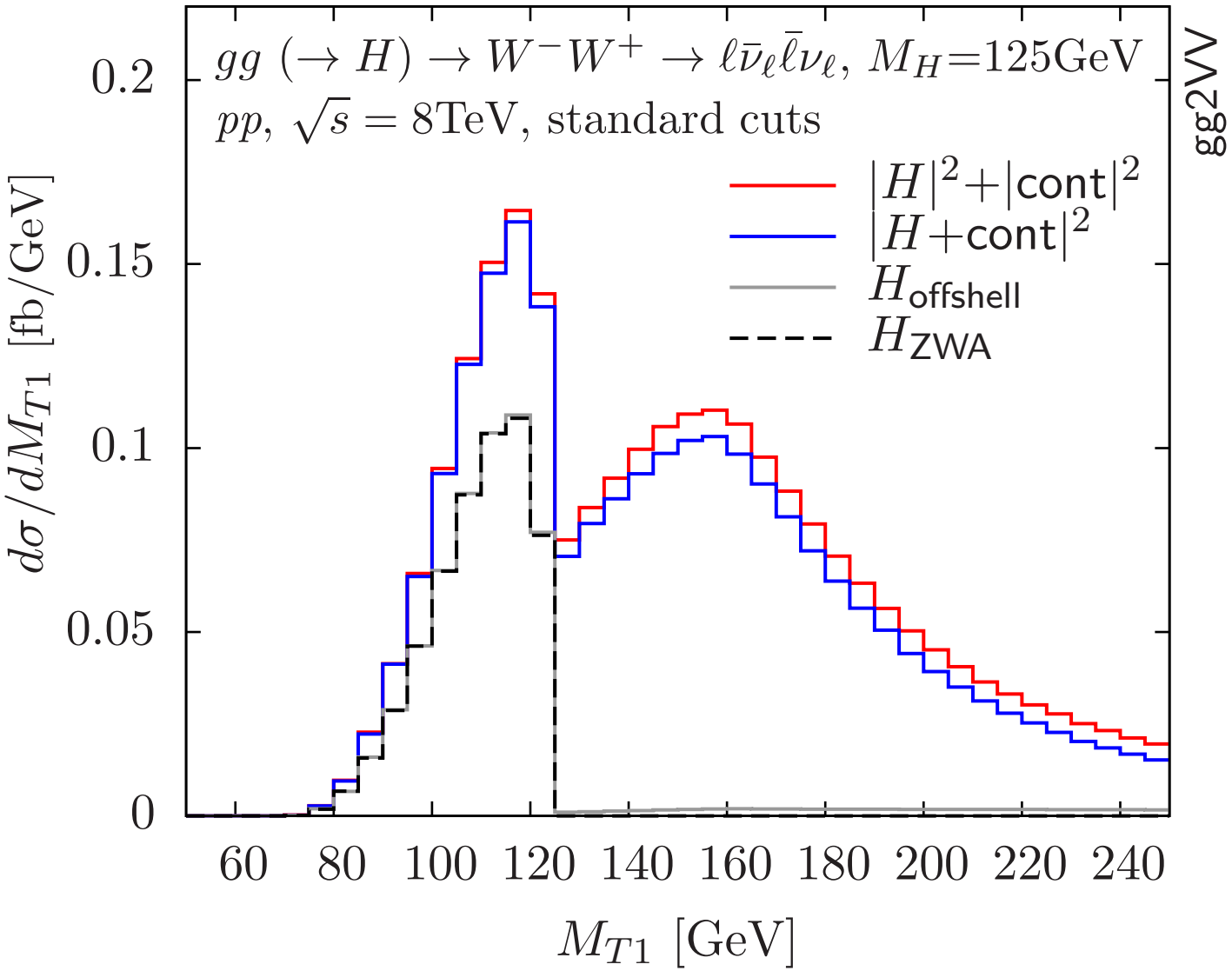

Standard cuts: $p_{T\ell} > 20\,\text{GeV}$, $|\eta_\ell| < 2.5$, $\not{p}_T > 30\,\text{GeV}$, $M_{\ell\ell} > 12\,\text{GeV}$




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




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




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

## Light Higgs analysis

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

| | $gg\,(\to H) \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ | | | | |
|---|---|---|---|---|---|
| | $\sigma$ [fb], $pp$, $\sqrt{s} = 8\,\text{TeV}$, $M_H = 125\,\text{GeV}$ | | | interference | |
| selection cuts | $H_{\text{offshell}}$ | 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. 10)

For comparison: different-flavour results (from p. 10):

| | $gg\,(\to H) \to WW \to \ell\bar{\nu}_\ell\bar{\ell}'\nu_{\ell'}$ | | | | |
|---|---|---|---|---|---|
| | $\sigma$ [fb], $pp$, $\sqrt{s} = 8\,\text{TeV}$, $M_H = 125\,\text{GeV}$ | | | interference | |
| selection cuts | $H_{\text{offshell}}$ | cont | $\lvert H_{\text{ofs}}\text{+cont}\rvert^2$ | $R_1$ | $R_2$ |
| standard cuts | 3.225(3) | 10.493(5) | 12.241(8) | 0.8923(7) | 0.542(3) |
| Higgs search cuts | 1.980(1) | 2.705(2) | 4.497(3) | 0.9599(7) | 0.905(2) |
| $+(0.75M_H < M_{T1} < M_H)$ | 1.779(1) | 0.6443(9) | 2.383(2) | 0.983(1) | 0.977(2) |

## Heavy Higgs analysis

# $gg \to H \to ZZ \to \ell\bar{\ell}\ell'\bar{\ell}'$ at $M_H = 400$ GeV

standard cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, $\quad 76$ GeV $< M_{\ell\bar{\ell}}, M_{\ell'\bar{\ell}'} < 106$ GeV

Higgs search cuts: standard cuts and $\boxed{|M_{\ell\bar{\ell}\ell'\bar{\ell}'} - M_H| < \Gamma_H}$

Settings: $\mu_R = \mu_F = M_H/2$ GeV, $\Gamma_H = 29.16$ GeV, MSTW2008LO, other: LHC Higgs Cross Section WG, arXiv:1101.0593 [hep-ph], App. A (with NLO $\Gamma_V$ and $G_\mu$ scheme)

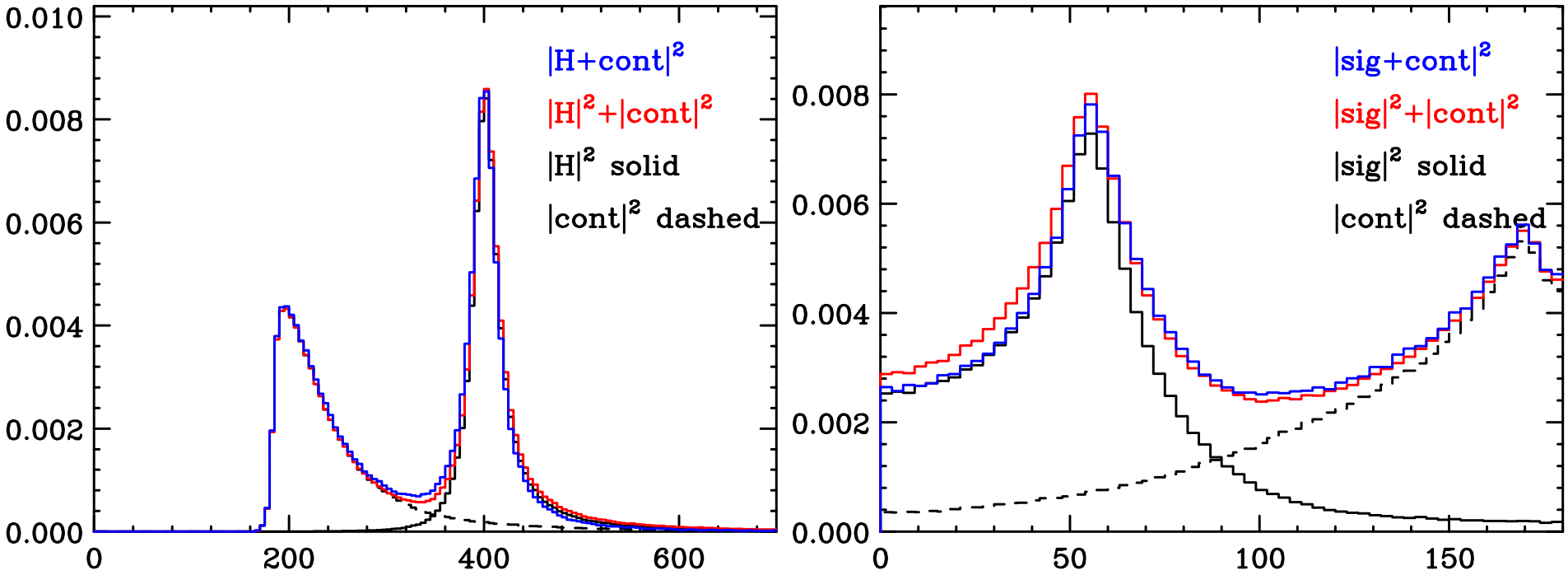
| | | $\sigma$ [fb], $pp$, $\sqrt{s} = 7$ TeV, $M_H = 400$ GeV | | | interference | |
|---|---|---|---|---|---|---|
| process | cuts | $\lvert\mathcal{M}_H\rvert^2$ | $\lvert\mathcal{M}_{\text{cont}}\rvert^2$ | $\lvert\mathcal{M}_H + \mathcal{M}_{\text{cont}}\rvert^2$ | $R_1$ | $R_2$ |
| $gg\ (\to H) \to ZZ$ | 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) |
| | | $\sigma$ [fb], $pp$, $\sqrt{s} = 14$ TeV, $M_H = 400$ GeV | | | interference | |
| process | cuts | $\lvert\mathcal{M}_H\rvert^2$ | $\lvert\mathcal{M}_{\text{cont}}\rvert^2$ | $\lvert\mathcal{M}_H + \mathcal{M}_{\text{cont}}\rvert^2$ | $R_1$ | $R_2$ |
| $gg\ (\to H) \to ZZ$ | 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) |

similar interference effects in $H \to ZZ \to \ell\bar{\ell}\ell\bar{\ell}$ and $\ell\bar{\ell}\nu_{\ell'}\bar{\nu}_{\ell'}$ (and $M_H = 500$ GeV or $\sqrt{s} = 8$ TeV)

MCFM team: thorough analysis of $gg \to H \to WW \to \ell\bar{\nu}_\ell\bar{\ell}'\nu_{\ell'}$ (diff. flavour), arXiv:1107.5569

## Heavy Higgs analysis

## $gg \to H \to ZZ \to \ell\bar{\ell}\ell'\bar{\ell}'$ at $M_H = 400\,\text{GeV}$



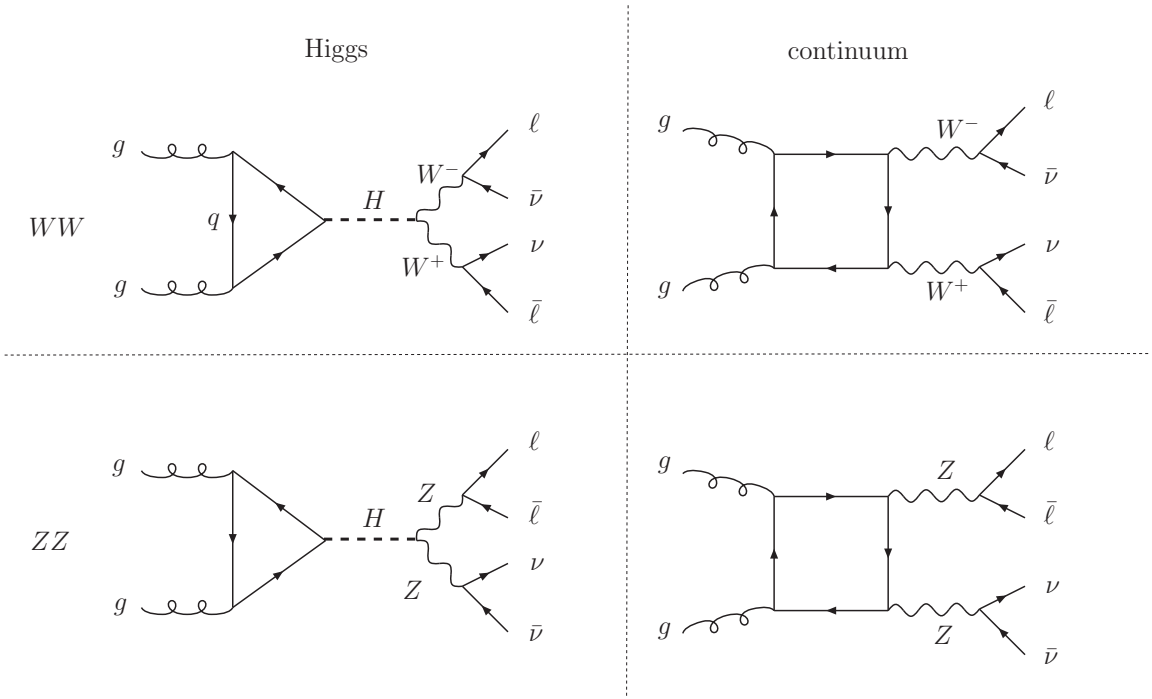

$M_{l\bar{l}l'\bar{l}'}$ [GeV] (left) and $\Delta\phi_{l\bar{l}}$ [°] (right) distributions [fb/[$\mathcal{O}$]]

LHC, 7 TeV, standard cuts

similar $M_{WW}$ distribution for $H \to WW$

# 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

| | $gg\,(\to H) \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ | | | | |
|---|---|---|---|---|---|
| | $\sigma$ [fb], $pp$, $\sqrt{s} = 8$ TeV, $M_H = 600$ GeV | | | interference | |
| process | $H_{\text{offshell}}$ | 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) |

| | $gg\,(\to H) \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ | | | | |
|---|---|---|---|---|---|
| | $\sigma$ [fb], $pp$, $\sqrt{s} = 8$ TeV, $M_H = 1000$ GeV | | | interference | |
| process | $H_{\text{offshell}}$ | 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

| | $gg\,(\to H) \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ | | | | |
|---|---|---|---|---|---|
| | $\sigma$ [fb], $pp$, $\sqrt{s} = 8$ TeV, $M_H = 600$ GeV | | | interference | |
| process | $H_{\text{offshell}}$ | 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) |

| | $gg\,(\to H) \to WW/ZZ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ | | | | |
|---|---|---|---|---|---|
| | $\sigma$ [fb], $pp$, $\sqrt{s} = 8$ TeV, $M_H = 1000$ GeV | | | interference | |
| process | $H_{\text{offshell}}$ | 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

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

# Outlook

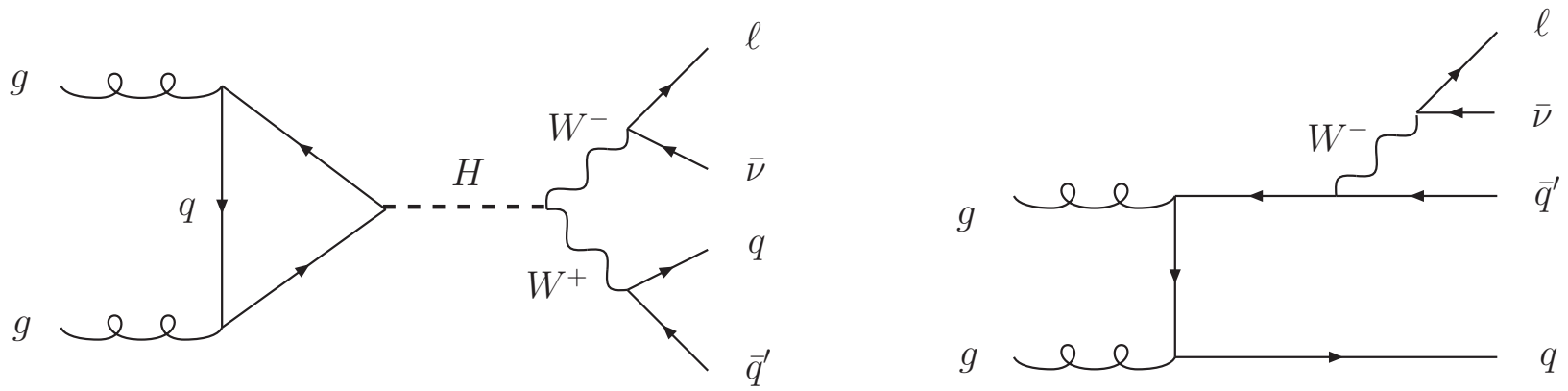
## Interference effects for semileptonic final states

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

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

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

interference with lower-order tree-level processes:



# Summary

- interference (and off-shell) effects essential to reach $1\%$ precision level
- $\mathcal{O}(5\text{–}10\%)$ corrections to inclusive $gg \to H \to VV$

  due to sizeable Higgs signal in region with invariant mass above $2M_V$

  even for $M_H = 125$ GeV
- $\mathcal{O}(100\%)$ corrections for very heavy Higgs signal
- experimental selection cuts allow to reduce/eliminate corrections
- $M_H = 125$ GeV: $4\ell$ is uncritical, $WW$: apply $M_{T1}$ cut
- heavy Higgs search: $4\ell$ is uncritical, $ZZ \to 2\ell 2\nu$: sizable effects with current selections (they should be improved)
- same-flavour $2\ell 2\nu$: need to take into account $WW/ZZ$ interference

  negative continuum $gg \to WW/ZZ$ interference of $\mathcal{O}(5\%)$
- gg2VV simulator available (parton-level integrator and event generator)
- wish list: NLO prediction for Higgs-continuum interference