Off-shell Higgs Production and Higgs Interference at the LHC: Overview

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Physics at TeV Colliders Workshop

Les Houches

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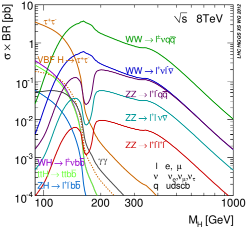
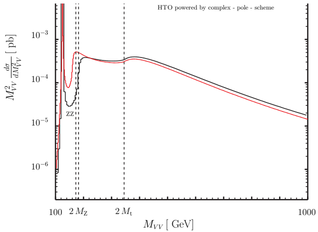
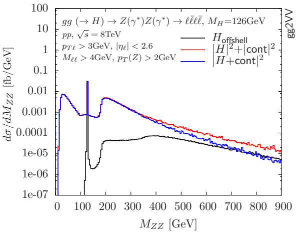
YR4 chapter (arXiv:1610.07922, 51 p.)

F. Caola, Y. Gao, NK, L. Soffi, J. Wang (eds.), A. Ballestrero, C. Becot, F. Bernlochner, H. Brun, A. Calandri, F. Campanario, F. Cerutti, D. de Florian, R. Di Nardo, L. Fayard, N. Fidanza, N. Greiner, A. V. Gritsan, G. Heinrich, B. Hespel, S. Höche, F. Krauss, Y. Li, S. Liebler, E. Maina, B. Mansoulié, C. O'Brien, S. Pozzorini, M. Rauch, J. Roskes, U. Sarica, M. Schulze, F. Siegert, P. Vanlaer, E. Vryonidou, G. Weiglein, M. Xiao, S. Yue

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

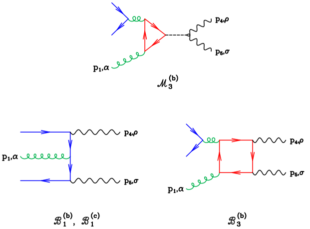


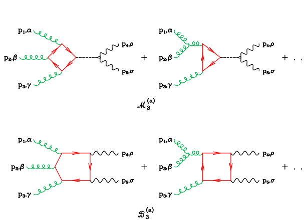


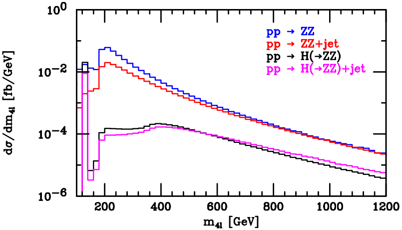


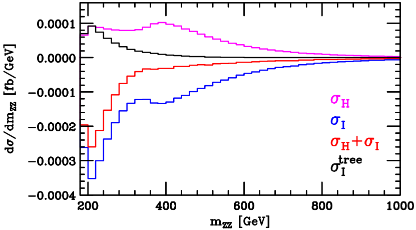
- $gg \to H \to VV \to 4\ell$ and $2\ell 2\nu$ signal-background interference very well studied at $\mathcal{O}(\alpha_s^2\alpha^4)$: Glover, van der Bij (1989); Kao, Dicus (1991); Binoth, Ciccolini, NK, Krämer (2006) (gg2WW); Campbell, Ellis, Williams (2011) (MCFM); NK (2012) (gg2VV); NK, Passarino (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

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)

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 $g_i \to \xi\, g_i,\quad g_f \to \xi\, g_f,\quad \Gamma_H \to \xi^4\,\Gamma_H$

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)

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

Matrix element method: optimize discrimination using fully differential information

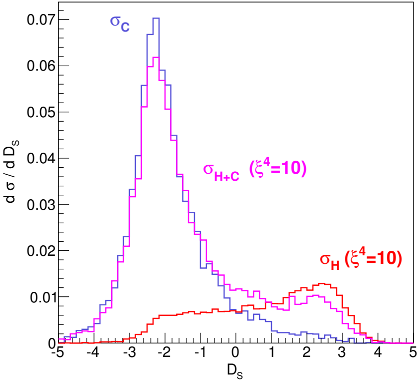
$P_{q\bar{q}}$: $q\bar{q}$ induced continuum background

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

P_H : gg induced Higgs amplitude squared

Discriminant:

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



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

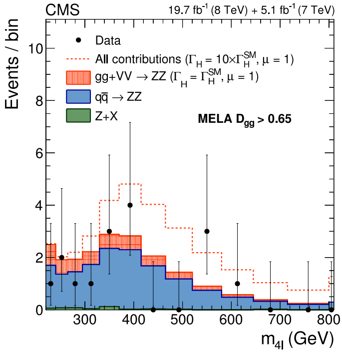
bound $1.6\times$ better than for $m_{4\ell} > 300$ GeV

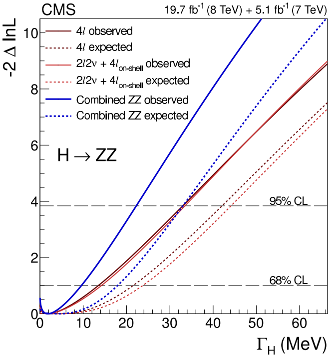
CMS analysis

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





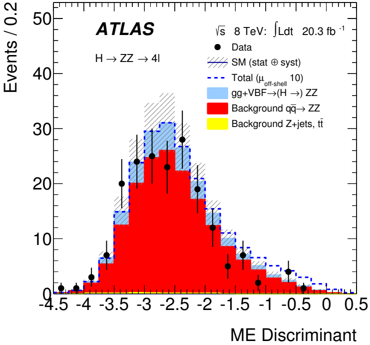
$$\Gamma_H < 5.4\, \Gamma_H^{SM} \text{ (95\% CL)}$$

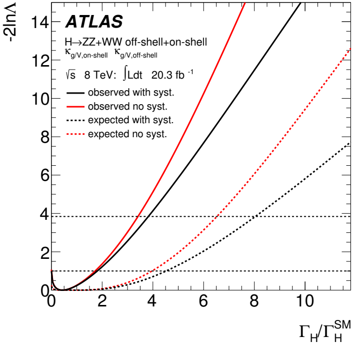
ATLAS analysis

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)





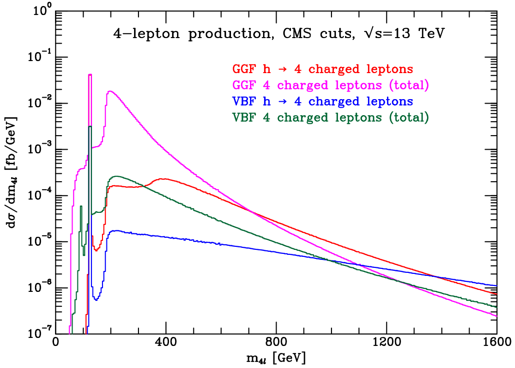
$$\Gamma_H < [4.5, 7.5]\ \Gamma_H^{SM} \quad \text{(95\% CL)}$$

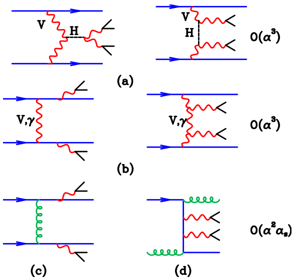
Higgs (width) constraints from vector boson fusion

off-shell effect also in VBF $H \to VV$: $\mathcal{O}(10\%)$ 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 $\sigma_{\text{prod}}(M_H)$)

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)



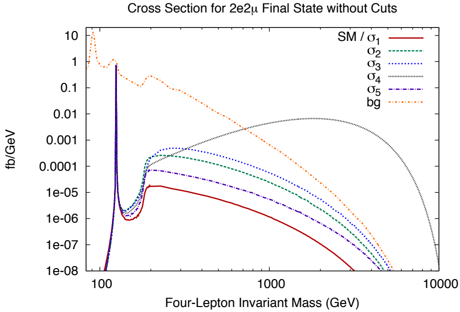


most sensitive off-sh. channel: $W^\pm W^\pm$
due to lower bkg. (t-channel Higgs!)

$\Gamma_H < 61\,\Gamma_H^{SM}$ (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 studies

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



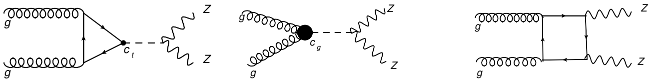
$\mathcal{O}_1 = -\frac{M_Z^2}{v} H Z_\mu Z^\mu$ (SM), $\mathcal{O}_2 = -\frac{1}{2v} H Z_{\mu\nu} Z^{\mu\nu}$, $\mathcal{O}_3 = -\frac{1}{2v} H Z_{\mu\nu} \widetilde{Z}^{\mu\nu}$, $\mathcal{O}_4 = \frac{M_Z^2}{M_H^2 v} Z_\mu Z^\mu \partial^2 H$,
$\mathcal{O}_5 = \frac{2}{v} H Z_\mu \partial^2 Z^\mu$ 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

and: $ggWW$ dimension-8 contact operators J. Bellm, S. Gieseke, N. Greiner, G. Heinrich, S. Plätzer, C. Reuschle, J. Felix von Soden-Fraunhofen arXiv:1602.05141

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

A. Azatov, C. Grojean, A. Paul, E. Salvioni (2014, update 2016)
(see also G. Cacciapaglia, A. Deandrea, G. Drieu La Rochelle, J. Flament (PRL 2014))

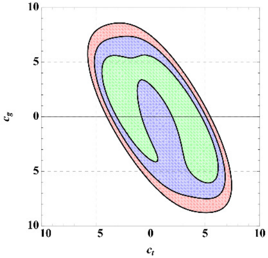


$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t}th + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu}G^{\mu\nu}$$

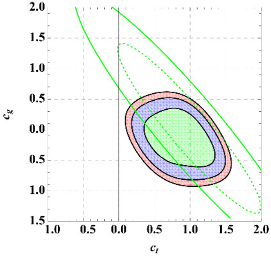
$$\mathcal{M}_{gg\to ZZ} = \mathcal{M}_h + \mathcal{M}_{bkg} = c_t \mathcal{M}_{c_t} + c_g \mathcal{M}_{c_g} + \mathcal{M}_{bkg}$$

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

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

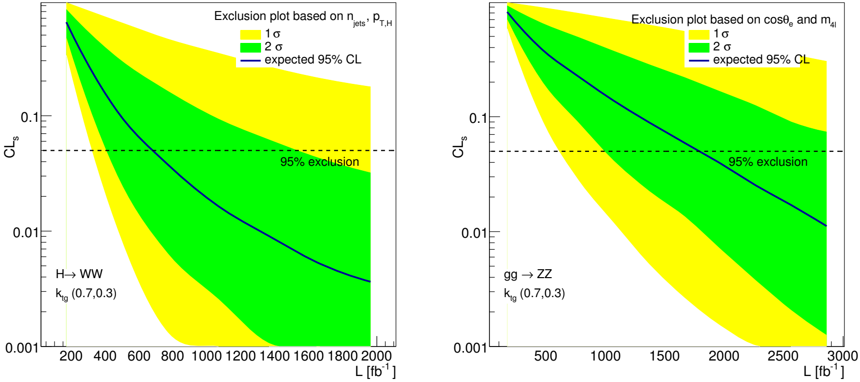


LHC 8 TeV CMS data



LHC 14 TeV 3 ab^{-1} data

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

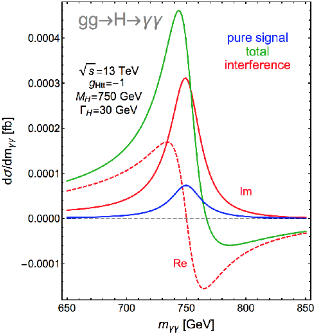


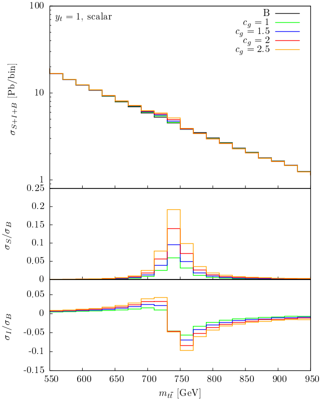
left: boosted analysis, right: off-shell analysis (not MELA improved)

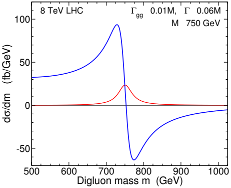
M. Buschmann, D. Goncalves, S. Kuttimalai, M. Schoenherr, F. Krauss, T. Plehn (2014) (1410.5806)

Heavy scalar (Φ) interference studies (2016)

- Signal-background interference in $gg\ (\to \Phi) \to \gamma\gamma$ ("750 GeV state") and $gg\ (\to \Phi) \to t\bar{t}$
  A. Djouadi, J. Ellis, J. Quevillon arXiv:1605.00542 (left fig.)
- Signal-background interference in $gg\ (\to \Phi) \to t\bar{t}$ with higher order QCD effects (simplified model and 2HDM) B. Hespel, F. Maltoni, E. Vryonidou arXiv:1606.04149 (center fig.)
- Higgs-Singlet Model interference effects with EFT operators (Φ-SM gauge bosons)
  S. Dawson, I.M. Lewis arXiv:1605.04944
- Signal-background interference for a singlet spin-zero digluon resonance S.P. Martin arXiv:1606.03026 (right fig.)



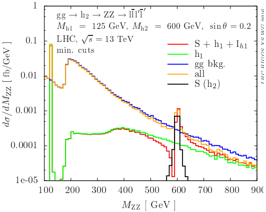


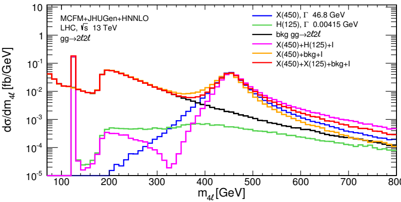


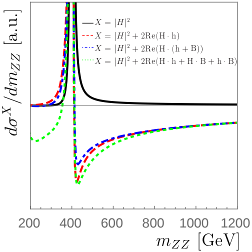
Heavy scalar interference studies (2015/16)

Heavy Higgs – background – light Higgs: non-trivial interference patterns

- Higgs Singlet Extension (ggF) NK, C. O'Brien arXiv:1502.04113 and YR4 (left fig.)
- Higgs Portal Scenario (ggF) C. Englert, I. Low, M. Spannowski arXiv:1502.04678
- Higgs Singlet Extension (VBF) A. Ballestrero, E. Maina arXiv:1506.02257 and YR4
- Higgs Singlet Extension (VBF) F. Campanario, M. Rauch YR4
- Generic couplings (tensor structure of HVV) Grisan, Sarica, Schulze, Xiao YR4 (center fig.)
- 2HDM: $gg(\to \{H, h\}) \to ZZ, WW$ interference effects N. Greiner, S. Liebler, G. Weiglein arXiv:1512.07232 (right fig.)
- Multiple heavy Higgs and BSM virtual contributions in $gg\ (\to \Phi) \to t\bar{t}$ M. Carena, Z. Liu arXiv:1608.07282







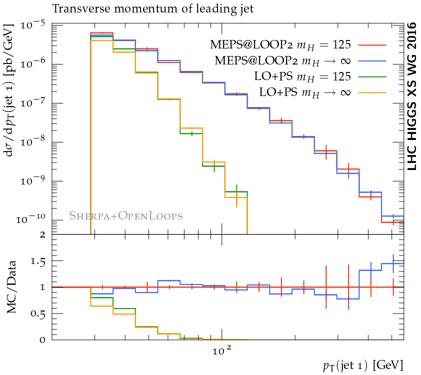
Matrix element–parton shower matching/merging

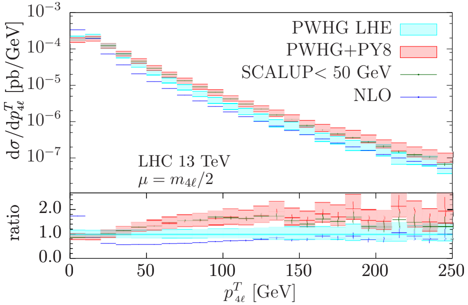
[LO(+partons)]+PS versus LO+PS

SHERPA+OPENLOOPS: $gg\ (\rightarrow H) \rightarrow Y$ vs. in addition $gg \rightarrow Yg$ and $qg \rightarrow Yq$ ($Y \equiv \ell\bar{\nu}_\ell\bar{\ell}'\nu_{\ell'}$, quark-loop amplitudes) merged with PS; harder p_T spectrum, overall: 10% effect from multi-jet merging Höche, Krauss, Pozzorini, Siegert arXiv:1309.0500 and YR4 (left fig.)

NLO+PS versus NLO

$gg \rightarrow ZZ \rightarrow 2\ell 2\ell'$ (without Higgs), PS effects for trans. mom. obs. ($p_{T,4\ell}$, p_{T,j_1}), but not for incl. obs. ($M_{4\ell}, \Delta\phi_{\ell\ell}$) S. Alioli, F. Caola, G. Luisoni, R. Röntsch arXiv:1609.09719 (right fig.)

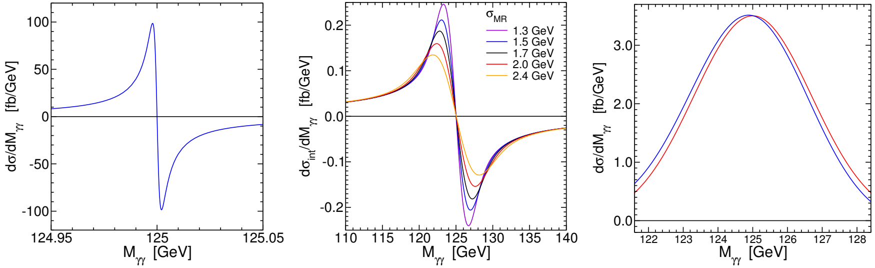




Higgs width via interferometry in $gg \to H \to \gamma\gamma$

S.P. 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})

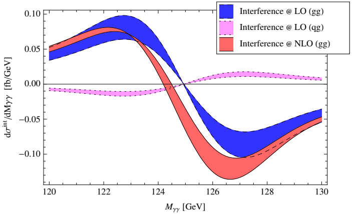
right fig.: peak shift of invariant mass distribution ($\sigma_{\text{MR}} = 1.7$ GeV): $\Delta M_{\gamma\gamma} = -120$ MeV at LO

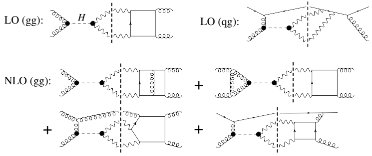
$(H \to \gamma\gamma)$+jet at LO: negligible mass peak shift (< 20 MeV for $p_{Tj} > 25$ GeV)

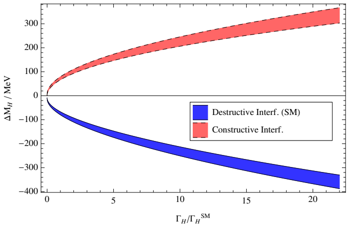
Daniel de Florian, et al. arXiv:1303.1397; S.P. Martin arXiv:1303.3342

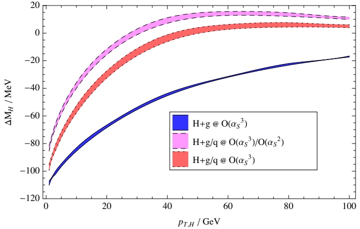
Higgs width via interferometry in $gg \to H \to \gamma\gamma$

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









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

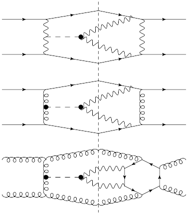
Vary Higgs width and couplings (maintaining on-peak SM signal strenghts):

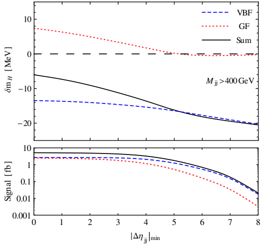
$$\Gamma_H < 15\,\Gamma_H^{SM}\ (14\text{ TeV},\ 3\text{ ab}^{-1},\ 95\%\text{ CL})$$

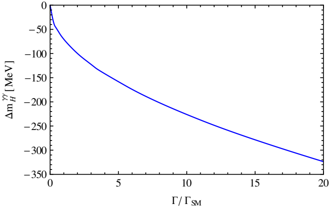
Higgs width via interferometry in $gg \to H \to \gamma\gamma$ with VBF $H \to \gamma\gamma$ mass peak as reference

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. Höche, H. Ita, Y. Li, J. Mazzitelli arXiv:1504.05215







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

$gg\ (\to H) \to \gamma\gamma$ interference @ full NLO (α_s^3), rate: -2%
$\mathcal{O}(40\%)$ scale uncertainty, kinematic dependence studied
J. Campbell, M. Carena, R. Harnik, Z. Liu arXiv:1704.08259

available in Sherpa 2.2 with Dire PS

also: ATLAS realistic peak shift study
with Sherpa 2.0& CSS PS
ATL-PHYS-PUB-2016-009
Becot, Bernlochner, Fayard, Yuen

$\Delta M_H = -35 \pm 9$ MeV

with variation $1 < K_{\text{bgk}} < K_{\text{sig}}$ at NNLO
(from known NLO) Bern, Dixon, Schmidt

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

Signal: (latest → talks of Stefano & Markus) $gg \to H$ 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 ~ 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%)

→ NLO QCD correction to $gg \to VV$ is of similar size or larger than residual scale uncertainty of $pp \to VV$ at NNLO QCD ⇒ 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:

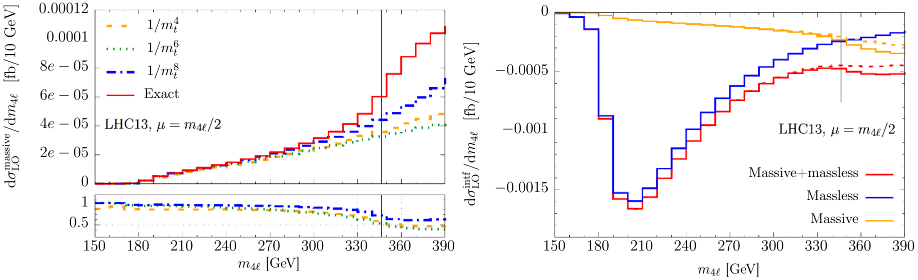
J. Campbell, K. Ellis, M. Czakon, S. Kirchner arXiv:1605.01380
on-shell Z's: $M_{ZZ} > 2M_Z$, extrapolation to $s \gg m_t^2$

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

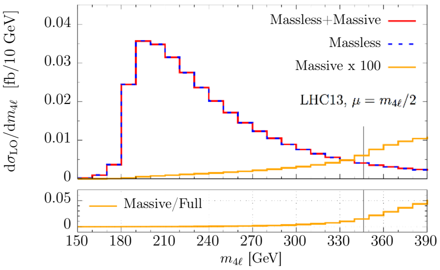
LO 4-lepton invariant mass distribution (massive: LME vs. exact),
left: background only, right: interference

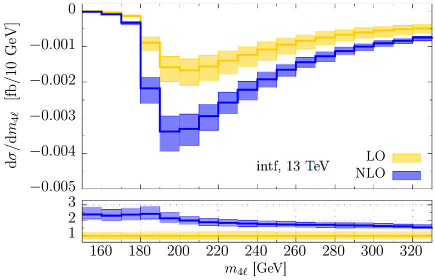


Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

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

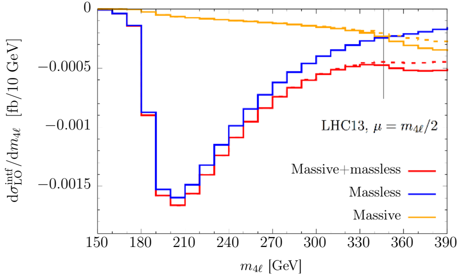
4-lepton invariant mass distributions, left: background only (LO),
right: interference with factor-2 scale variation (lower panel: K-factor)

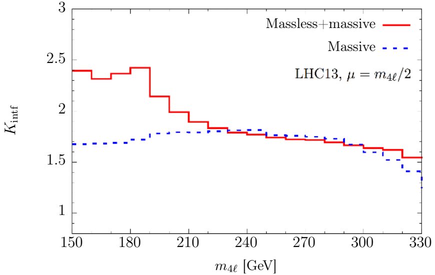




Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

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

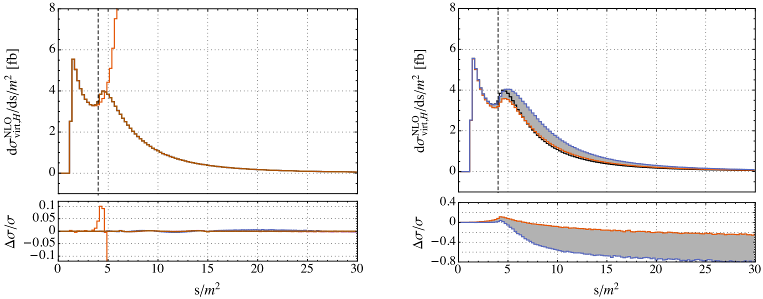
Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

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.

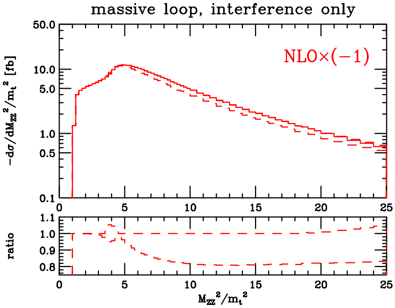


similar behaviour found when comparing for LO $gg \to ZZ$ continuum

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

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

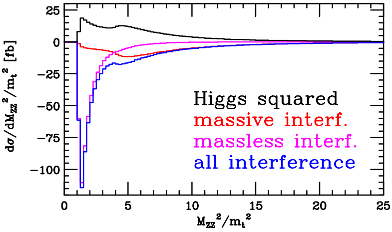
Uncertainty on NLO interference due to improved LME ($\lesssim 20\%$ on approximated part):

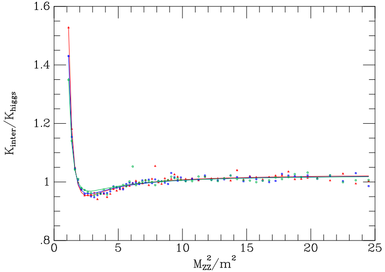


Precision predictions for $gg\ (\to H) \to VV$ signal-background interference

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

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





Implementing loop-induced @ NLO in MC tools

Automated loop-induced @ LO

- MG5_aMC (OLP MadLoop): Hirschi, Mattelaer arXiv:1507.00020
- similar capability in Sherpa+OpenLoops (e.g. arXiv:1309.0500) and GoSam (e.g. arXiv:1512.07232, arXiv:1602.05141)
- ...

Implementing loop-induced @ NLO in MC tools

- POWHEG: Alioli, Caola, Luisoni, Röntsch arXiv:1609.09719
- MG5_aMC: in progress
  Hirschi, Mattelaer, Vryonidou, NK, Shivaji, Mandal, ...
  Method 1: reweighting (arXiv:1607.00763)
  Method 2: direct integration in MadFKS
  Feasibility study for $gg \to (\gamma \to e^+e^-)(\gamma \to \mu^+\mu^-)$ completed
- Sherpa: in progress Kuttimalai, ... (Catani-Seymour)
- Herwig7+GoSam: in progress
- ...

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 (rather than cut away), provides complementary physics information (similar at high-energy linear collider)
- $gg \to H \to ZZ, WW \to 4$ leptons: signal-background interference studied in detail, mature MC tools available at LO; complete NLO calculations available (2-loop multi-scale!, still some approx.), PS matching demonstrated
- First analysis of interference (& Higgs width bounds) for $pp \to H \to ZZ$ + jet
- Studies of heavy Higgs-light Higgs-background 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 $\to$ 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

Future directions and discussion points

- Tools: high-mass NLO $gg \to VV$ (exact?) matched/merged with PS
  $\to$ public event generators for experimental studies
  (HERWIG7, MG5_AMC, POWHEG, SHERPA, ...)
- Comparing NLO+PS with (merged) LO+PS predictions
- qg effects at NLO (overlap with $pp \to VV$ @ N^{3}LO)
- finite top mass corrections
- EW corrections
- BSM/EFT constraints