Theory Higgs: Lineshape and Interference

Nikolas Kauer
Royal Holloway, University of London

Higgs Hunting 2017
Orsay–Paris, France
July 24, 2017
Outline

- HXSWG YR4: Off-shell Higgs and Higgs interference
- Recap and Recent/Ongoing Work
  - $H \to ZZ, WW (+\text{jets})$ in ggF & VBF: sizeable off-shell Higgs signal contribution with large signal-backg. interference
  - Higgs width measurement in a nutshell, $\Gamma_H$ bound at the LHC
  - BSM/EFT: exploiting the off-shell $H \to VV$ region
  - BSM: heavy scalar–light Higgs–background interference effects
  - Higgs width constraints from $gg \to H \to \gamma\gamma$
  - Precision predictions for $gg (\to H) \to VV$ interference/backg.
- Matrix element–parton shower matching/merging
- Implementing loop-induced @ NLO in MC tools
- Summary and future directions
I.8.3 $H \rightarrow VV$ modes ($V = W, Z$)

I.8.3.1 Input parameters and recommendations for the QCD scale and the order of the gluon PDF

I.8.3.2 Off-shell and interference benchmark cross sections and distributions: Standard Model

I.8.3.3 Off-shell and interference benchmark cross sections and distributions: 1-Higgs Singlet Model

I.8.3.4 Multijet merging effects in $gg \rightarrow \ell\bar{\nu}_\ell \ell'\nu_{\ell'}$ using SHERPA

I.8.3.5 Study of higher-order QCD corrections in the $gg \rightarrow H \rightarrow VV$ process

I.8.3.6 Higgs boson off-shell simulation with the MCFM and JHU generator frameworks

I.8.3.7 Interference contributions to gluon-initiated heavy Higgs production in the 2HDM using GoSAM

I.8.4 $gg \rightarrow VV$ at NLO QCD

I.8.4.1 The status of theoretical predictions

I.8.4.2 Brief description of the NLO computation for $gg \rightarrow 4l$

I.8.4.3 Results and recommendation for the $gg (\rightarrow H) \rightarrow ZZ$ interference $K$-factor

I.8.5 $H \rightarrow \gamma\gamma$ mode

I.8.5.1 Theory overview, I.8.5.2 Monte Carlo interference implementations

I.8.5.3 Studies from ATLAS
$gg \rightarrow H \rightarrow ZZ, WW$: sizeable off-shell Higgs signal with large signal-background interference

- $gg \rightarrow H \rightarrow VV \rightarrow 4\ell$ 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 ($gg \rightarrow VV$ parton-calculators and event generators), MadGraph5, Sherpa+OpenLoops (allows for merging of $gg \rightarrow VV + \{0, 1\}$ jets)

- loop technology closing in on calculation at $\mathcal{O}(\alpha_s^3 \alpha^4)$ (see below) Aachen/FNAL/IPPP, Karlsruhe, Zurich

Interference for $pp \rightarrow H \rightarrow ZZ + \text{jet}$

$ZZ$ and $ZZ + \text{jet}$ cross sections are comparable ($p_T^{\text{jet}} > 30 \text{ GeV}$)

Campbell, R.K. Ellis, Furlan, Röntsch

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

Higgs width measurement in a nutshell

- Total Higgs width $\Gamma_H$ 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: $\Gamma_H < 1.1$ GeV, but note that $\Gamma_{H,SM} \approx 4$ MeV)

- All resonant Higgs cross sections depend on $\Gamma_H$, therefore $\Gamma_H$ 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 $\Gamma_H$ ($\Gamma_H = \mathcal{O}(\Gamma_{H,SM})$) M. Peskin (2012); B. Dobrescu, J. Lykken (2013)


- $e^+e^-\rightarrow Z(H \rightarrow \text{all})$: 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: $\Gamma_H$ 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


\[ |\mathcal{M}_{i \rightarrow H \rightarrow f}|^2 = \frac{|\mathcal{M}_i|^2 |\mathcal{M}_f|^2}{|p_H^2 - M_H^2 + i M_H \Gamma_H|^2} \]

resonance contribution to signal cross section (“on-peak”):

NWA scaling degeneracy: \( \sigma \) unchanged if \( g_i \rightarrow \xi g_i, \ g_f \rightarrow \xi g_f, \ \Gamma_H \rightarrow \xi^4 \Gamma_H \)

see L. Dixon, Y. Li arXiv:1305.3854 (or below, p. 18)

\[ \sqrt{p_H^2 - M_H} \gg \mathcal{O}(\Gamma_H) \rightarrow p_H^2 - M_H^2 \gg M_H \Gamma_H \rightarrow |\mathcal{M}_{i \rightarrow H \rightarrow f}|^2 \approx \frac{|\mathcal{M}_i|^2 |\mathcal{M}_f|^2}{|p_H^2 - M_H^2|^2} \]

off-resonance contribution (“off-peak”):

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 ($H \rightarrow ZZ$)

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:

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

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

bound $1.6 \times$ better than for $m_{4\ell} > 300$ GeV
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 \( (P_H \rightarrow P_{gg}) \), backgrounds fully considered

\[
\Gamma_H < 5.4 \Gamma_H^{SM} \quad (95\% \text{ CL})
\]
improvements:

- similar to CMS, thorough consideration of systematic uncertainties
- provide results as function of the unknown $gg \rightarrow ZZ$ 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)

\[ \Gamma_H < [4.5, 7.5] \Gamma_H^{SM} \] (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 $\sigma_{\text{prod}}(M_H)$)


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

Off- & on-shell $\Gamma_H$ bound not strictly model independent ($E$-dependent Higgs couplings?)


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 (next slides)

Cross Section for 2e2$\mu$ Final State without Cuts

O$_1$ = $-\frac{M_Z^2}{v} H Z_\mu Z^\mu$ (SM),
O$_2$ = $-\frac{1}{2v} H Z_{\mu\nu} Z^{\mu\nu}$,
O$_3$ = $-\frac{1}{2v} H Z_{\mu\nu} \tilde{Z}^{\mu\nu}$,
O$_4$ = $\frac{M_Z^2}{M_H^2 v} Z_\mu Z^\mu \partial^2 H$,
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 $\rightarrow$ good control with 300 fb$^{-1}$  I. Anderson et al.  arXiv:1309.4819

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

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

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

\[
\mathcal{M}_{gg\rightarrow ZZ} = \mathcal{M}_h + \mathcal{M}_{bg} = c_t \mathcal{M}_{ct} + c_g \mathcal{M}_{cg} + \mathcal{M}_{bg}
\]

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

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

LHC 8 TeV CMS data
LHC 14 TeV 3 ab$^{-1}$ data
Effective $ggH$ coupling: boosted v. off-shell Higgs sensitivity

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

Heavy scalar ($\Phi$) interference studies (2016)

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

- Signal-background interference in $gg \rightarrow \Phi \rightarrow \gamma\gamma$ (“750 GeV state”) and $gg \rightarrow \Phi \rightarrow t\bar{t}$
  A. Djouadi, J. Ellis, J. Quevillon arXiv:1605.00542 (left fig.)
- Signal-background interference in $gg \rightarrow \Phi \rightarrow t\bar{t}$ 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 ($\Phi$-SM gauge bosons)
- 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 (VBF) A. Ballestrero, E. Maina arXiv:1506.02257 and YR4
- Higgs Singlet Extension (VBF) F. Campanario, M. Rauch YR4
- Generic couplings (tensor structure of $HVV$) Gritsan, Sarica, Schulze, Xiao YR4 (center fig.)
- 2HDM: $gg \rightarrow \{H, h\} \rightarrow ZZ, WW$ interference effects N. Greiner, S. Liebler, G. Weiglein arXiv:1512.07232 (right fig.)
- 2HDM: $pp \rightarrow \Phi \rightarrow t\bar{t}$ @ NLO QCD W. Bernreuther, P. Galler, C. Mellein, Z.G. Si, P. Uwer arXiv:1511.05584, arXiv:1702.06063
- Multiple heavy Higgs and BSM virtual contributions in $gg \rightarrow \Phi \rightarrow t\bar{t}$ M. Carena, Z. Liu arXiv:1608.07282
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 $gg \to H \to ZZ^*$)

![Graphs]

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

center fig.: interference contribution (real term) for different mass resolutions (Gaussian, $\sigma_{\text{MR}}$)

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

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

Precision predictions for $gg (\rightarrow H) \rightarrow \gamma\gamma$ signal-background interference

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 strengths):

$$\Gamma_H < 15 \Gamma_H^{SM} \quad (14 \text{ TeV}, 3 \text{ ab}^{-1}, 95\% \text{ CL})$$
Higgs width via interferometry in $gg \rightarrow H \rightarrow \gamma\gamma$
with VBF $H \rightarrow \gamma\gamma$ mass peak as reference

Calculation of $pp \rightarrow H \rightarrow \gamma\gamma$ signal (VBF and GF) and interference with background (LO)


\[ \Delta m_{\gamma\gamma} \equiv \delta m_{\gamma\gamma}^{H+X,NLO,incl} - \delta m_{\gamma\gamma}^{H+2j,LO,VBF \text{ cuts}} \]

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

\[ \Delta M_H = -35 \pm 9 \text{ MeV} \]
with variation $1 < K_{bgk} < K_{sig}$ at NNLO
(from known NLO) Bern, Dixon, Schmidt
Precision predictions for \( gg (\rightarrow H) \rightarrow \gamma\gamma \) signal-background interference

NLO+NLL \( q_T \) resummation for \( gg(\rightarrow H) \rightarrow \gamma\gamma \) interference

L. Cieri, F. Coradeschi, D. de Florian, N. Fidanza  \( \text{arXiv:1706.07331} \)

NLO+NLL \( q_T \) resummation formalism, based on

- Bozzi, Catani, de Florian, Grazzini  \( \text{arXiv:hep-ph/0508068} \)
- Catani, Cieri, de Florian, Ferrera, Grazzini  \( \text{arXiv:1311.1654} \)

Uncertainty bands from varying \( \mu_R/F \) and resummation scale as

\[ \mu_R = 2m_H, \mu_F = m_H/2 \text{ and } \mu_R = m_H/2, \mu_F = 2m_H \text{ with } \mu_{\text{res}} \in [m_H/4, m_H] \]

Setup: \( \sqrt{s} = 8 \text{ TeV} \), MSTW 2008 MSTW  \( \text{arXiv:0901.0002} \), cuts: \( q_T,\gamma_1 > 40 \text{ GeV} \), \( q_T,\gamma_2 > 30 \text{ GeV} \), smooth cone Frixione  \( \text{arXiv:hep-ph/9801442} \) \( n = 1, E_{\text{max}} = 3 \text{ GeV} \), \( R = 0.4 \)

Resummation distributes events from \( q_T = 0 \) to finite \( q_T \rightarrow \) negative interference contribution shifted towards larger \( q_T \) (uncertainty more realistic due to same effect).
Precision predictions for $gg (\rightarrow H) \rightarrow \gamma\gamma$ signal-background interference

NLO+NLL $q_T$ resummation for $gg(\rightarrow H) \rightarrow \gamma\gamma$ interference

L. Cieri, F. Coradeschi, D. de Florian, N. Fidanza  
arXiv:1706.07331

Resummed prediction (dark blue) of $q_T$-vetoed cross section yields smaller mass peak shift than fixed-order result (red), compatible with zero at low end, as the ratio of real interference $R/S$ becomes small for small $q_T^{H,\text{max}}$.

Resummed prediction of $q_T$-region above veto stable at small $q_T \rightarrow \text{again brought about by redistribution of events from } q_T = 0 \text{ to finite } q_T$. 
Precision predictions for $gg \rightarrow H \rightarrow \gamma\gamma$ signal-background interference

$gg \rightarrow H \rightarrow \gamma\gamma$ interference @ full NLO ($\alpha_s^3$)

J. Campbell, M. Carena, R. Harnik, Z. Liu  

(building on L. Dixon, M.S. Siu  

rate: $-2\%$, $\mathcal{O}(40\%)$ scale uncertainty, kinematic dependence studied

![Graph showing precision predictions for $gg \rightarrow h(125 \text{ GeV}) \rightarrow \gamma\gamma$.](image)

Higgs width bounds from total rate change may be feasible
Precision predictions for \(gg \rightarrow H \rightarrow VV\) signal-background interference

**Signal:** (latest → talk of Massimiliano) \(gg \rightarrow H\) 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 \(M_t \rightarrow \infty\) (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)


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

11–17\% (9–12%) NNLO QCD correction to \(pp \rightarrow ZZ\) \((WW)\) for \(\sqrt{s} = 7–14\) TeV
\(gg \rightarrow VV\) contributes to full NNLO correction to \(pp \rightarrow ZZ\) \((WW)\) with 60\% (35%) \(\Rightarrow\) NLO QCD correction to \(gg \rightarrow VV\) is of similar size or larger than residual scale uncertainty of \(pp \rightarrow VV\) at NNLO QCD \(\Rightarrow\) calculation is important and by a similar argument the calculation of the NLO QCD correction to signal-background interference
Precision predictions for \( gg (\rightarrow H) \rightarrow VV \) signal-background interference

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

NLO and NNLO calculation for \( gg (\rightarrow H) \rightarrow WW \rightarrow \ell\nu\ell\nu \) interference with \( M_H = 600 \) GeV in soft-gluon approximation (very good accuracy for inclusive signal cross section)


\( gg \rightarrow VV \) continuum background beyond leading order, i.e. beyond \( \mathcal{O}(\alpha_s^2) \):

Precision predictions for $gg (\rightarrow H) \rightarrow VV$

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%)

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

$gg \rightarrow ZZ$: recent, complementary extensions to high orders ($\sim 6$) 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 $s \gg m_t^2$

off-shell $Z$’s including leptonic decays for $s \lesssim (2m_t)^2$
Precision predictions for $gg (\rightarrow H) \rightarrow VV$
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 $gg (\rightarrow H) \rightarrow VV$

signal-background interference

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

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

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

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

$K_{\text{intf}} \approx \sqrt{K_{\text{signal}} K_{\text{bkg}}}$ for full considered $m_{4\ell}$ range
Precision predictions for $gg \rightarrow H \rightarrow VV$

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 $gg \rightarrow ZZ$ continuum
Precision predictions for $gg (\rightarrow H) \rightarrow VV$ 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 $gg (\rightarrow H) \rightarrow VV$

signal-background interference

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

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

Higgs squared
massive interf.
massless interf.
all interference
Matrix element–parton shower matching/merging
[LO(+partons)]+PS versus LO+PS

**SHERPA+OPENLOOPS:** $gg \to H \to Y$ vs. in addition $gg \to Yg$ and $qg \to Yq$ ($Y \equiv \ell \bar{\ell} \ell' \bar{\ell'}$, 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**

$gg \to ZZ \to 2\ell 2\ell'$ (without Higgs), PS effects for trans. mom. obs. ($p_T, A_\ell, p_T,j_1$), 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.)

$gg \to H \to \gamma \gamma$ including interference available in SHERPA: fixed order and matched to PS (MC@NLO) S. Höche et al., ATLAS studies C. Becot, L. Fayard, et al. ATL-PHYS-PUB-2016-009
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 GO\_SAM (e.g. arXiv:1512.07232, arXiv:1602.05141)
- ...

Implementing loop-induced @ NLO in MC tools

- 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 $gg \rightarrow (\gamma \rightarrow e^+e^-)(\gamma \rightarrow \mu^+\mu^-)$ completed
- SHERPA: in progress Kuttimalai, ... (Catani-Seymour)
- HERWIG7+GO\_SAM: in progress
- ...

Summary

- \( H \rightarrow ZZ, WW \) 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)
- \( gg \rightarrow H \rightarrow ZZ, WW \rightarrow 4 \) 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 \( pp \rightarrow H \rightarrow ZZ + \text{jet} \)
- Studies of heavy Higgs-light Higgs-background interference effects in \( gg \rightarrow H \rightarrow VV \), 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 → provides complementary constraints on Higgs couplings and Higgs width \( \Gamma_H \) (when combined with on-peak data)
- Assuming no \( E \)-dependence of relevant Higgs couplings, a bound on \( \Gamma_H \) 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)
- \( H \rightarrow \gamma\gamma \): 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 \( H \rightarrow VV \) EFT and BSM benchmark studies
Future directions

- Tools: high-mass NLO $gg \rightarrow VV$ (exact?) matched/merged with PS
  → 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 $pp \rightarrow VV$ @ $N^3$LO)
- finite top mass corrections
- EW corrections
- BSM/EFT constraints