Higgs interference effects at NLO

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Narrow width approximation

NWA: Factorize production and decay

\[ gg \rightarrow H \rightarrow VV \quad gg \rightarrow H \quad H \rightarrow VV \]

\[ \frac{\Gamma_H}{m_H} \sim 10^{-5} \]

**BUT:** 10\% of events in \( H \rightarrow VV \) above 2\( m_V \) threshold

(Kauer, Passarino '12)

\[ \text{NWA not sufficient} \] to describe behavior of \( H \rightarrow VV \)
Beyond the NWA

Consistent treatment requires both signal and background amplitudes

\[ |A_{ZZ}|^2 = |A_H|^2 + |A_b|^2 + 2\text{Re}[A_H A_b^*] \]

\[ \rightarrow \sigma_{\text{full}} = \sigma_{\text{sigl}} + \sigma_{\text{bkgd}} + \sigma_{\text{intf}} \]
Interference effect and line shape

Interference is strong and destructive, especially at high invariant mass

Campbell, Ellis, Williams ‘13
Understanding high energy behavior

Cut open top loop – have $t\bar{t} \rightarrow VV$

- **Signal** and **background** amplitudes-squared grow like $E^2$
- **Interference** grows like $-E^2 \rightarrow$ cancels $E^2$ terms of signal and background
- **Higgs unitarizing massive scattering amplitude** – connected to its role in EWSB and mass generation

\[ aE^2 + (b + c)m_t E \]
\[ -aE^2 + (d - c)m_t E \]
\[ -(b + d)m_t E \]
Using off-shell Higgs

Off-shell Higgs events provide a new tool for studying Higgs physics

- High mass behavior probes unitarization properties of Higgs
  - As important as measuring Higgs couplings for understanding EWSB
  - Cross sections small $\rightarrow$ HL-LHC

- Higgs couplings more sensitive to NP at high energies

Campbell, Ellis, Williams ‘13
Using off-shell Higgs: indirect width constraints

- Observation of Caola & Melnikov:
  \[ \sigma_{on} \propto g_i^2 g_f^2 / \Gamma_H \quad \sigma_{off} \propto g_i^2 g_f^2 \]
  \[ \Rightarrow \Gamma_H \propto \frac{\sigma_{off}}{\sigma_{on}} \quad \text{indirect constraint on width} \]

- CMS: \( \Gamma_H < 13 \) MeV  \quad \text{ATLAS: } \Gamma_H < 23 \) MeV

- Direct constraints \( \sim 1 \) GeV

- Compare with SM value: \( \Gamma_H \approx 4 \) MeV
Indirect Higgs width constraint: 
\textit{caveat emptor}

Indirect constraints not model-independent:

- \textbf{Assume same couplings on- & off-shell}
- Can construct models with $\Gamma_H > \Gamma_H^{SM}$ but no sensitivity from off-shell measurements (Englert, Spannowksy ‘14)
- Possible option:
  - Introduce energy-dependent couplings in $\kappa$-framework / EFT (Englert, Soreq, Spannowsky ‘14)
  - Constrain couplings and width simultaneously
  - Highly non-trivial dependence of signal, background and interference on these couplings! (see e.g. Azatov, Grojean, Paul, Salvioni ‘16)
Impact of higher order corrections

• Signal (incl. top mass effects) known at NLO
  – NLO corrections large, k-factor $\sim 1.7$

• Experimental analyses use background and interference at LO only
  – NLO corrections approximated by corrections from signal
    adds uncertainties to analysis

• Recent work has extended background and interference to NLO

  Campbell, Czakon, Ellis, Kirchner, hep-ph/1605.01380
  Caola, Dowling, Melnikov, R.R., Tancredi, hep-ph.1605.04610
Higgs Interference Effects at NLO

Known

Massless: known
Massive: extremely difficult / impossible

Known

Massless: easy
Massive: moderate

Known

Known

Spira, Djouadi, Graudenz, Zerwas ‘95; Harlander, Kant ‘05; Aglietti, Bonciani, Degrassi, Vicini ‘07;
Ellis, Hinchliffe, Soldate, v.d. Bij ‘88;
Caola et al ‘15, v. Manteuffel, Tancredi ‘15
Hagiwara, Kuruma, Yamada ‘91; Campbell, Ellis, Zanderighi ‘07;
v.d. Bij, Glover ‘89;

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Higgs interference effects at NLO
$gg \rightarrow (H) \rightarrow ZZ$: Top Mass Expansion

Expand in $s/m_t^2$

- Keep terms to $(s/m_t^2)^4$
- Expect to be valid for partonic energies $s \lesssim 4m_t^2$

Dowling, Melnikov ‘15
Validity of top mass expansion

Can check validity at LO:

- Good approximation below $2m_t$ threshold

- Restricted to $m_{4\ell} \leq 2m_t$, $p_{T,j} < 150$ GeV

- Cannot probe unitarization effects :(

- Large window $150$ GeV $\lesssim m_{4\ell} \lesssim 2m_t$ where Higgs is off-shell and we can study interference effects at NLO
Parameters

- $gg \to ZZ \to e^+e^-\mu^+\mu^-$ at 13 TeV LHC
- Dynamical scale $\mu_F = \mu_R = \{m_{4\ell}/4, m_{4\ell}/2, m_{4\ell}\}$
- Minimal cuts:
  - $150 \text{ GeV} \leq m_{4\ell} \leq 340 \text{ GeV}$
  - $p_{T,j} < 150 \text{ GeV}$
  - $60 \text{ GeV} \leq m_{\ell\ell} \leq 120 \text{ GeV}$
$gg \to (H) \to ZZ$ Results: Cross Sections

$$
\begin{align*}
\sigma_{LO}^{signal} &= 0.043^{+0.012}_{-0.009} \text{ fb,} \\
\sigma_{LO}^{bkgd} &= 2.90^{+0.77}_{-0.58} \text{ fb,} \\
\sigma_{LO}^{inf} &= -0.154^{+0.031}_{-0.04} \text{ fb,} \\
\sigma_{LO}^{full} &= 2.79^{+0.74}_{-0.56} \text{ fb,} \\
\sigma_{NLO}^{signal} &= 0.074^{+0.008}_{-0.008} \text{ fb,} \\
\sigma_{NLO}^{bkgd} &= 4.49^{+0.34}_{-0.38} \text{ fb,} \\
\sigma_{NLO}^{inf} &= -0.287^{+0.031}_{-0.037} \text{ fb,} \\
\sigma_{NLO}^{full} &= 4.27^{+0.32}_{-0.35} \text{ fb,}
\end{align*}
$$

- **Destructive interference $\sim 5\%$**
  - $\sim 4 \times$ larger than signal, order of magnitude smaller than background
  - Can use specialized cuts needed to enhance relative to signal and background

- **Scale uncertainty: $20\%$-$30\%$ at LO, $10\%$ at NLO**

- $K_{sigl} = 1.72 \quad K_{bkgd} = 1.55 \quad K_{inf} = 1.65 \sim \sqrt{K_{sigl}K_{bkgd}}$
$gg \rightarrow (H) \rightarrow ZZ$ Results: Mass distributions

- Differential k-factors relatively flat...
- Except for interference near $2m_Z$ threshold
$gg \rightarrow (H) \rightarrow ZZ$ Results:
Differential $k$-factor

- Massless loop dominates near $2m_Z$ threshold, drives $k$-factor behavior
Comparison with similar work

Campbell, Czakon, Ellis, Kirchner, hep-ph/1605.01380

- Only interference contribution considered
- On-shell Z bosons, so $m_{ZZ} > 2m_Z$
- Massive two-loop amplitudes computed in mass expansion to $(s/m_t^2)^6$
- Massive real emission amplitudes computed exactly – no need for jet cut
- Results extended beyond $2m_t$ threshold using Padé approximations – look at high-mass tail
Comparison with similar work

Campbell, Czakon, Ellis, Kirchner, arXiv:1605.01380

Qualitatively similar behavior of k-factors near $2m_Z$ threshold

k-factor flat in high-energy tail
$gg \to (H) \to WW$

- Analogous to $gg \to (H) \to ZZ$
- Mass expansion more complicated since top and bottom quarks mix in loop
  - $\rightarrow$ neglect 3rd generation altogether
    - Comparable to massless contribution at low-intermediate $m_{T,WW}$
    - Dominate at high $m_{T,WW}$
- Partial results only

- $gg \to W^+W^- \to \nu_e e^+\mu^-\bar{\nu}_\mu$
- No kinematic cuts imposed
- Scales as for $ZZ$
\[ gg \rightarrow (H) \rightarrow WW \] Results: Cross Sections

\[
\begin{align*}
\sigma_{\text{signal}}^{\text{LO}} &= 48.3^{+10.4}_{-8.4} \text{ fb}, \\
\sigma_{\text{signal}}^{\text{NLO}} &= 81.0^{+10.5}_{-8.2} \text{ fb} \\
\sigma_{\text{bkgd}}^{\text{LO}} &= 49.0^{+12.8}_{-9.7} \text{ fb}, \\
\sigma_{\text{bkgd}}^{\text{NLO}} &= 74.7^{+5.5}_{-6.2} \text{ fb} \\
\sigma_{\text{intf}}^{\text{LO}} &= -2.24^{+0.44}_{-0.59} \text{ fb}, \\
\sigma_{\text{intf}}^{\text{NLO}} &= -4.15^{+0.47}_{-0.54} \text{ fb} \\
\sigma_{\text{full}}^{\text{LO}} &= 95.0^{+22.6}_{-17.6} \text{ fb}, \\
\sigma_{\text{full}}^{\text{NLO}} &= 151.6^{+15.4}_{-13.9} \text{ fb}.
\end{align*}
\]

- **Destructive interference \sim 2\%**
  - Higgs peak present \rightarrow interference smaller than signal and background
- **Scale uncertainty reduced by factor \sim 2**
- \( K_{\text{sigl}} = 1.68 \quad K_{\text{bkgd}} = 1.53 \quad K_{\text{intf}} = 1.85 \)
  - \rightarrow slightly above geometric mean
gg → (H) → WW Results:
Mass distributions

- Differential k-factors relatively flat...
- … except for interference near $2m_W$ threshold – as in ZZ case
$gg \to (H) \to WW$ Results: Estimating effect of 3$\text{rd}$ generation

- As in ZZ case, enhancement from massless loops
- 3$\text{rd}$ generation loops give relatively flat differential k-factor
  → estimate by using LO results scaled by approximate k-factor

$$\sqrt{K_{\text{sigl}}K_{\text{bkgd}}}$$
Conclusions

- Higgs off-shell behavior provides a rich environment to study Higgs physics:
  - Probe **unitarizing behavior** of the Higgs
  - **Indirect constraints** on Higgs width
  - **Test couplings** at high energies
- NLO corrections to interference in $gg \rightarrow ZZ$ and $gg \rightarrow WW$, are now known, at least below $2m_t$ threshold
- Difficulty of computing two-loop massive corrections
  - top mass expansion for $ZZ$
  - neglect 3$^{rd}$ generation for $WW$
- $ZZ$ in window $150 \text{ GeV} \leq m_{4\ell} \leq 340 \text{ GeV}$
  - Moderate k-factors $\sim 1.6-1.7$
  - $K_{intf} \sim \sqrt{K_{sig}K_{bkgd}}$ except near $2m_Z$ threshold -- driven by massless amplitudes
- $WW$:
  - Interference k-factor slightly larger than signal and background k-factors
  - Effect of 3$^{rd}$ generation at NLO approximated assuming uniform contribution to k-factor
THANK YOU!