Offshell Higgs production and interference effects at NLO

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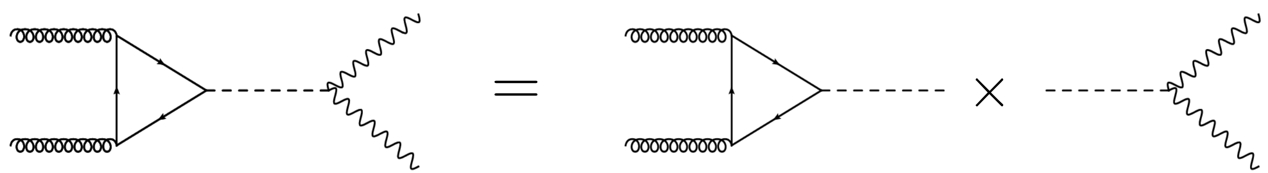
Higgs on- and offshell

- Higgs discovery was the highlight of Run I.
- Higgs physics continues to be focus during Run II – precise measurements of properties
- $H \to VV$ important decay channel
- Higgs properties mostly probed using **onshell Higgs**
  - Factorize production and decay



$$gg \to H \to VV \qquad gg \to H \qquad H \to VV$$

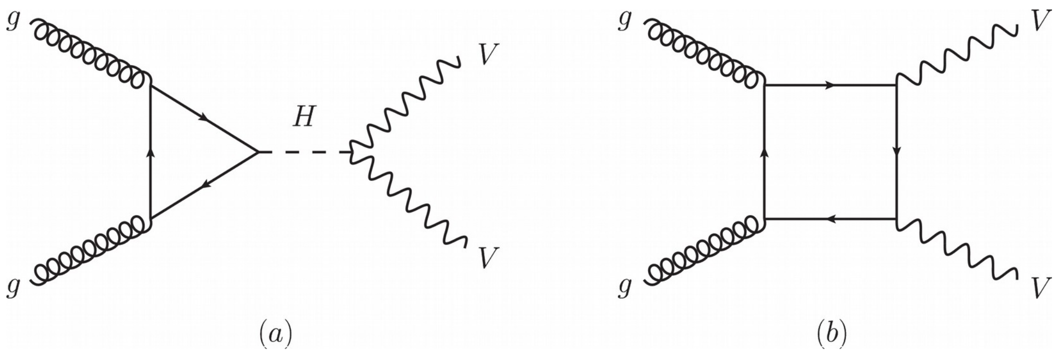
  - Treat signal and background separately

BUT: 10% of events in $H \to VV$ above $2m_V$ threshold (Kauer, Passarino '12)

→ NWA **not sufficient** to describe behavior of $H \to VV$

Offshell interference

Consistent treatment in **high mass region** requires both signal and background amplitudes

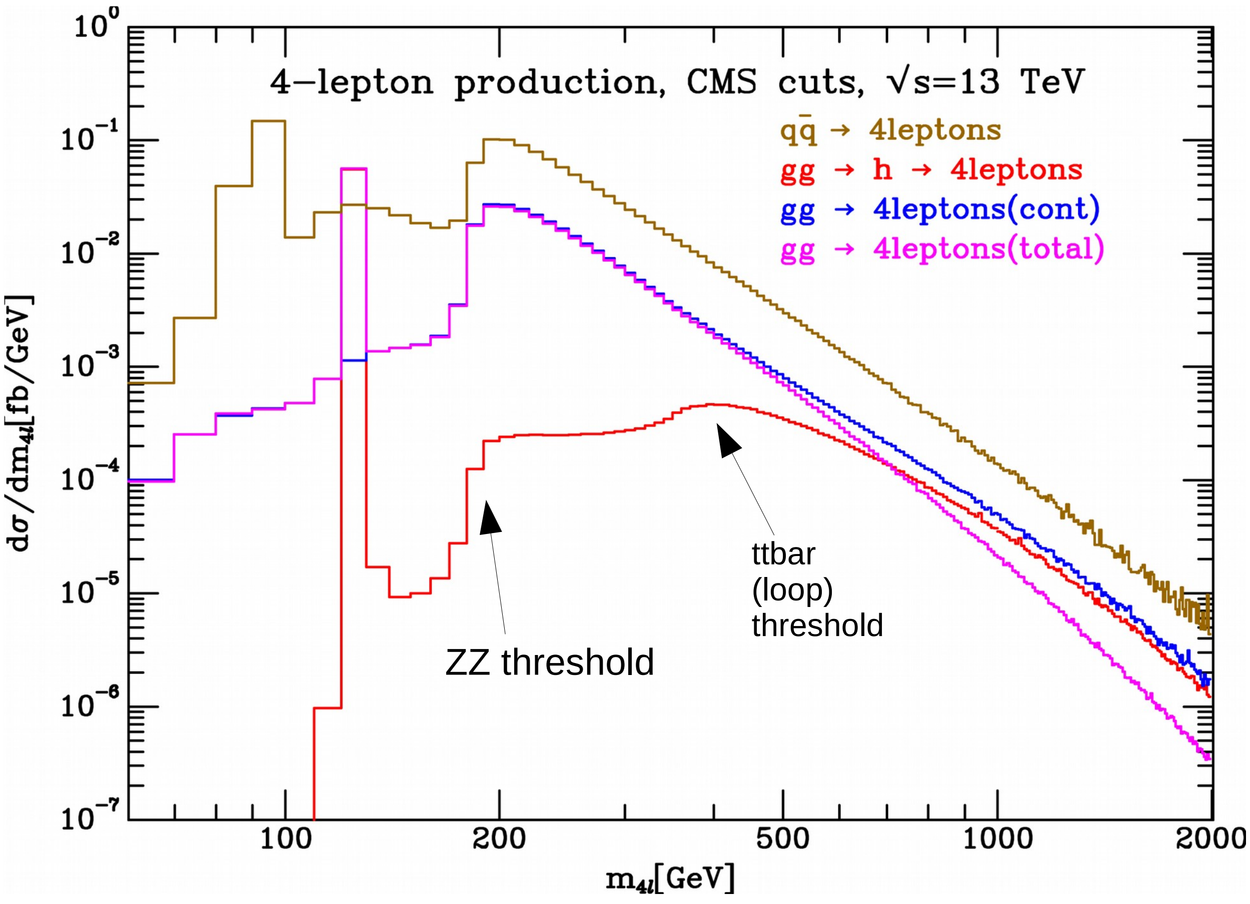


“signal” A_H “background” A_b

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

$$\to \sigma_{\mathrm{full}} = \sigma_{\mathrm{sigl}} + \sigma_{\mathrm{bkgd}} + \sigma_{\mathrm{intf}}$$

Interference effect and line shape

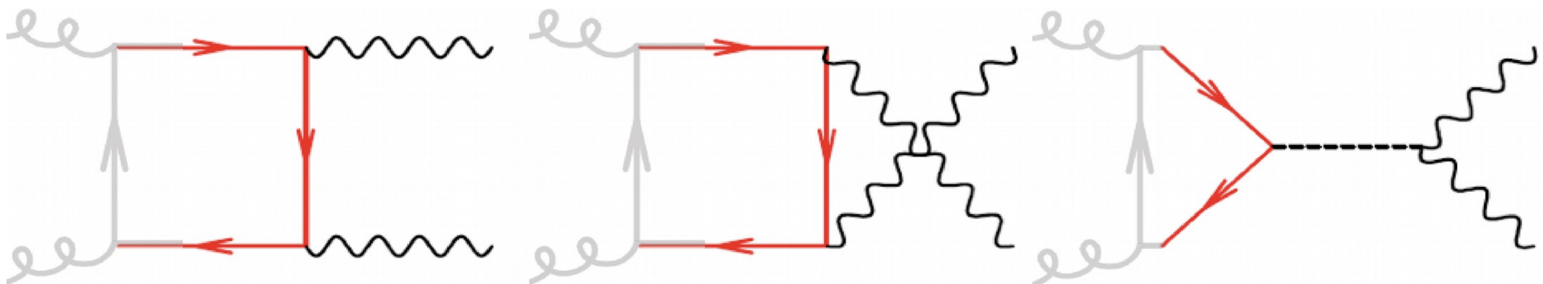


Campbell, Ellis, Williams ‘13

Interference is **strong** and **destructive,** especially at high invariant mass

Understanding high energy behavior

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



$aE^2 + (b+c)m_t E$ $\quad -aE^2 + (d-c)m_t E$ $\quad -(b+d)m_t E$

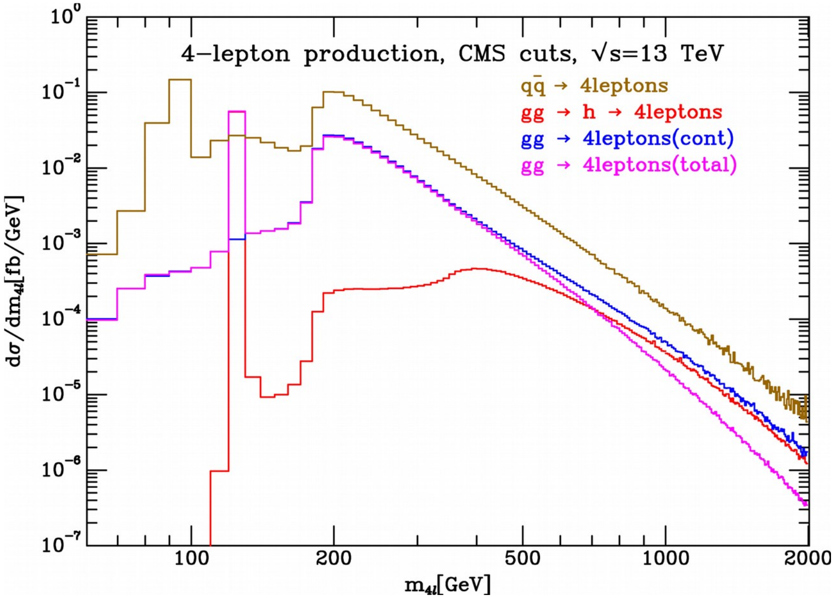
J. Campbell

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

Using off-shell Higgs

We have **a new tool** for studying Higgs physics!

- High mass behavior probes **unitarization properties** of Higgs
  - Important for understanding EWSB
  - Cross sections small → 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:

$$\sigma_{\text{on}} \propto g_i^2 g_f^2 / \Gamma_H \qquad \sigma_{\text{off}} \propto g_i^2 g_f^2$$

$$\Rightarrow \Gamma_H \propto \frac{\sigma_{\text{off}}}{\sigma_{\text{on}}}$$ → **indirect constraint on width**

- CMS: $\Gamma_H < 13 \text{ MeV}$ ATLAS: $\Gamma_H < 23 \text{ MeV}$
- Direct constraints ~ 1 GeV
- Compare with SM value: $\Gamma_H \approx 4 \text{ MeV}$

Indirect Higgs width constraint: *caveat emptor*

Indirect constraints not model-independent:

- **Assume same couplings on- & off-shell**
- Can construct models with $\Gamma_H > \Gamma_H^{\mathrm{SM}}$ but no sensitivity from off-shell measurements (Englert, Spannowsky '14)
- Possible option:
  - Introduce energy-dependent couplings in κ-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)
  - CMS: simultaneous constraints on width & *HVV* coupling (hep-ex/1507.06656)

Impact of higher order corrections

- Signal (incl. top mass effects) known at **NLO**
  - **NLO corrections large,** k-factor ~ 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

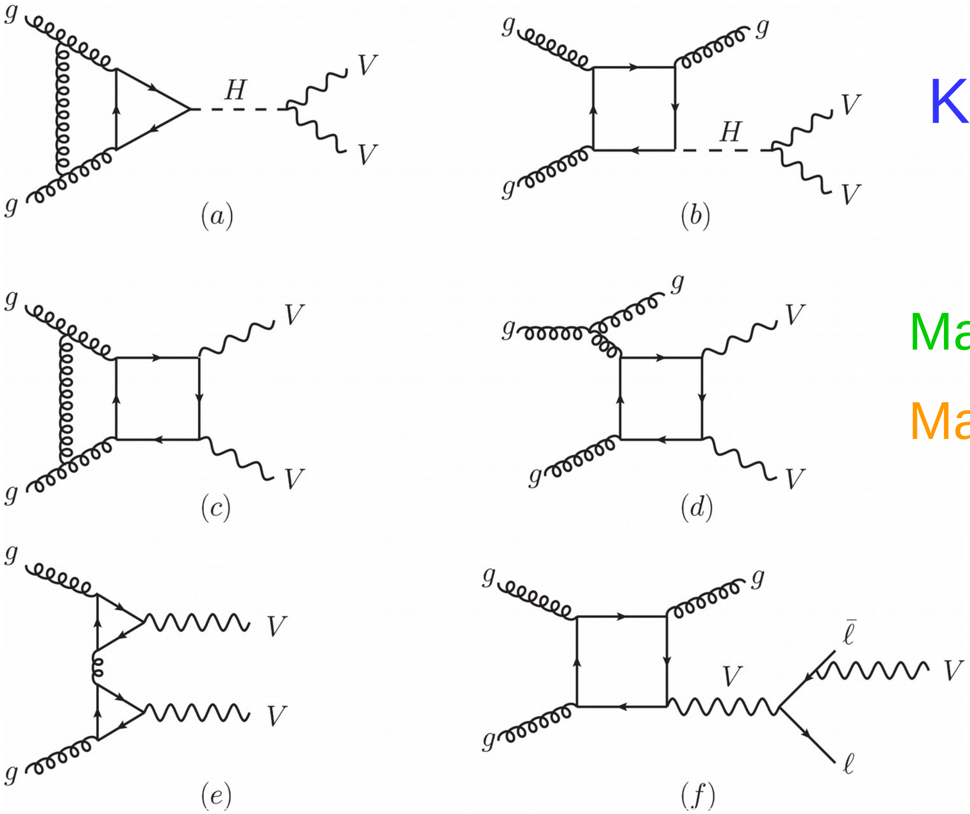
Higgs Interference Effects at NLO

Known

Massless: known

Massive: extremely difficult / impossible

Known



Known

Massless: easy

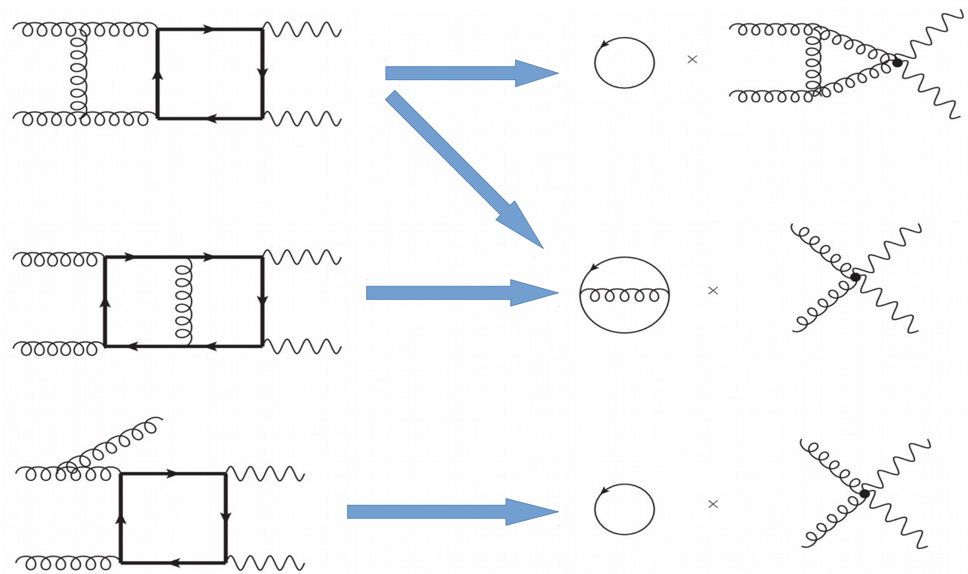
Massive: moderate

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;

$gg \to (H) \to ZZ$: Top Mass Expansion

Expand in s/m_t^2

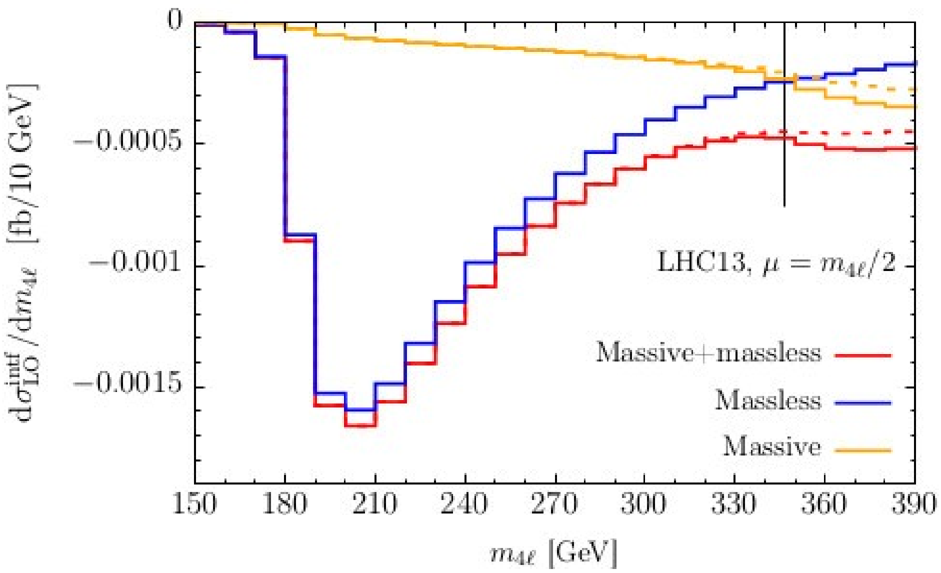


- Keep terms to $\left(s/m_t^2\right)^4$
- Expect to be valid for partonic energies $s \lesssim 4m_t^2$

Dowling, Melnikov '15

Validity of top mass expansion

Can check validity at LO – Interference for exact m_t dependence vs mass expansion



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 $150\ \mathrm{GeV} \lesssim m_{4\ell} \leq 2m_t$ 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

$$\sigma^{\rm signal}_{\rm LO} = 0.043^{+0.012}_{-0.009}\ {\rm fb}, \qquad \sigma^{\rm signal}_{\rm NLO} = 0.074^{+0.008}_{-0.008}\ {\rm fb}$$

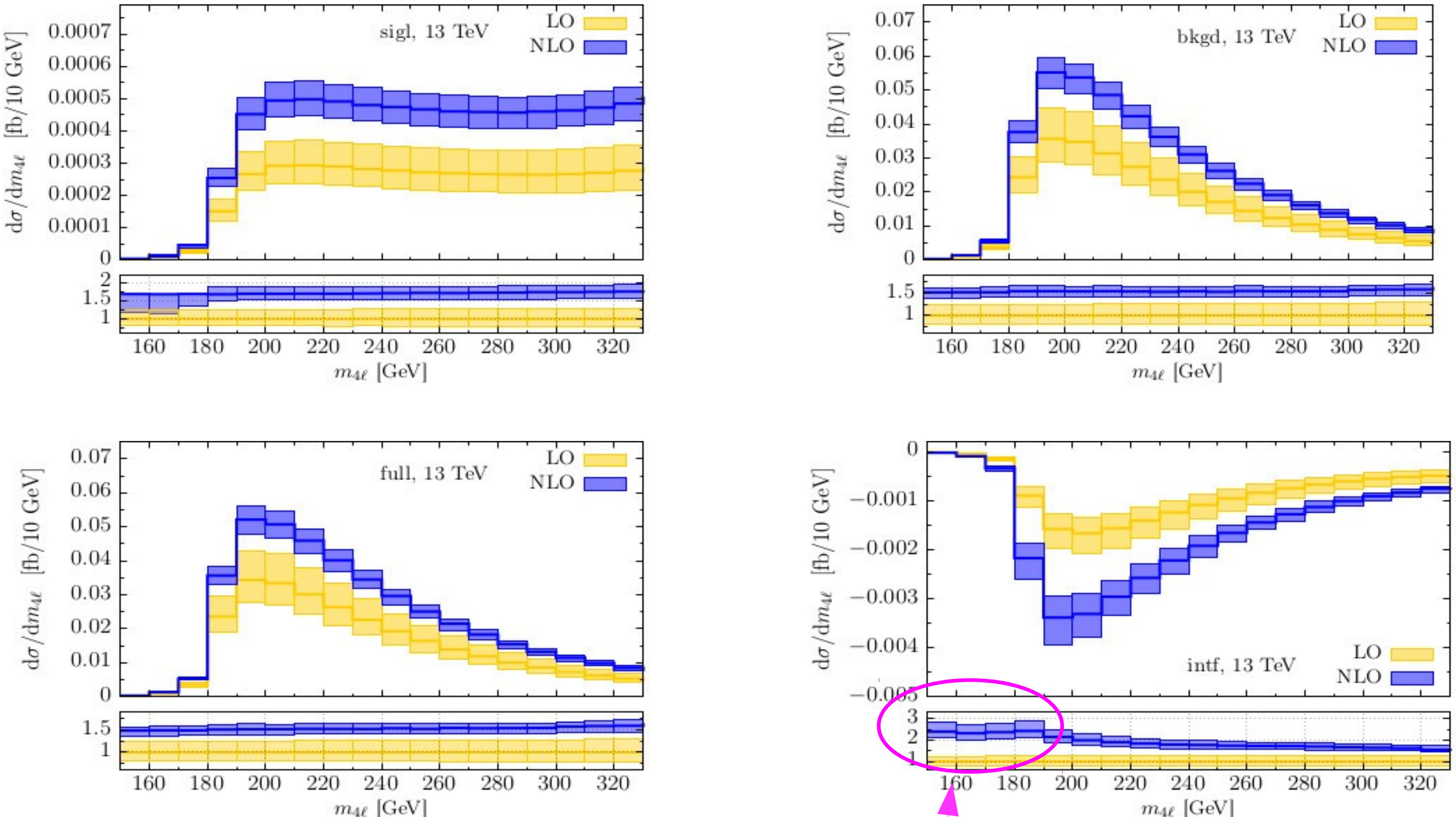
$$\sigma^{\rm bkgd}_{\rm LO} = 2.90^{+0.77}_{-0.58}\ {\rm fb}, \qquad \sigma^{\rm bkgd}_{\rm NLO} = 4.49^{+0.34}_{-0.38}\ {\rm fb}$$

$$\sigma^{\rm intf}_{\rm LO} = -0.154^{+0.031}_{-0.04}\ {\rm fb}, \qquad \sigma^{\rm intf}_{\rm NLO} = -0.287^{+0.031}_{-0.037}\ {\rm fb}$$

$$\sigma^{\rm full}_{\rm LO} = 2.79^{+0.74}_{-0.56}\ {\rm fb}, \qquad \sigma^{\rm full}_{\rm NLO} = 4.27^{+0.32}_{-0.35}\ {\rm fb},$$

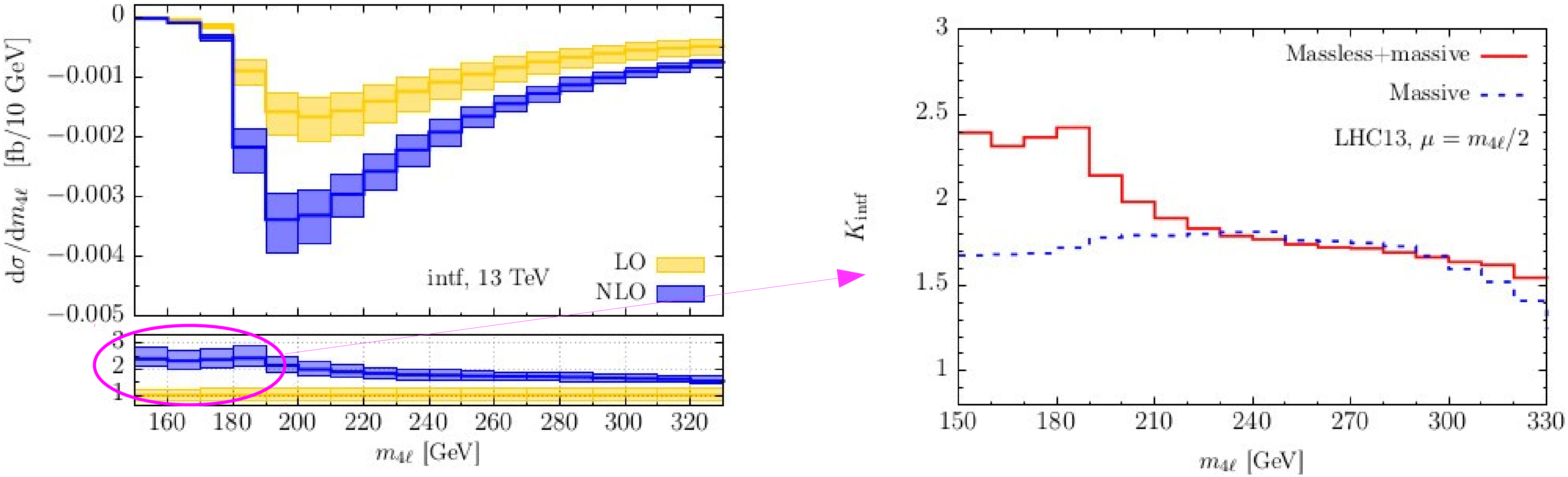
- ~ 13k events at HL-LHC (3 ab^{-1})
- Destructive interference ~ **5%**
  - ~ 4 x larger than signal, order of magnitude smaller than background
  - Can use specialized cuts needed to enhance relative to signal and background
- Scale uncertainty: 20%-30% at LO, 10% at NLO
- $K_{\rm sigl} = 1.72 \qquad K_{\rm bkgd} = 1.55 \qquad K_{\rm intf} = 1.65 \simeq \sqrt{K_{\rm sigl} K_{\rm bkgd}}$

$gg \rightarrow (H) \rightarrow ZZ$ Results: Mass distributions



- Differential k-factors relatively flat...
- Except for interference near $2m_Z$ threshold

$gg \to (H) \to ZZ$ Results: Differential k-factor



- Massless loop dominates near $2m_Z$ threshold, drives k-factor behavior

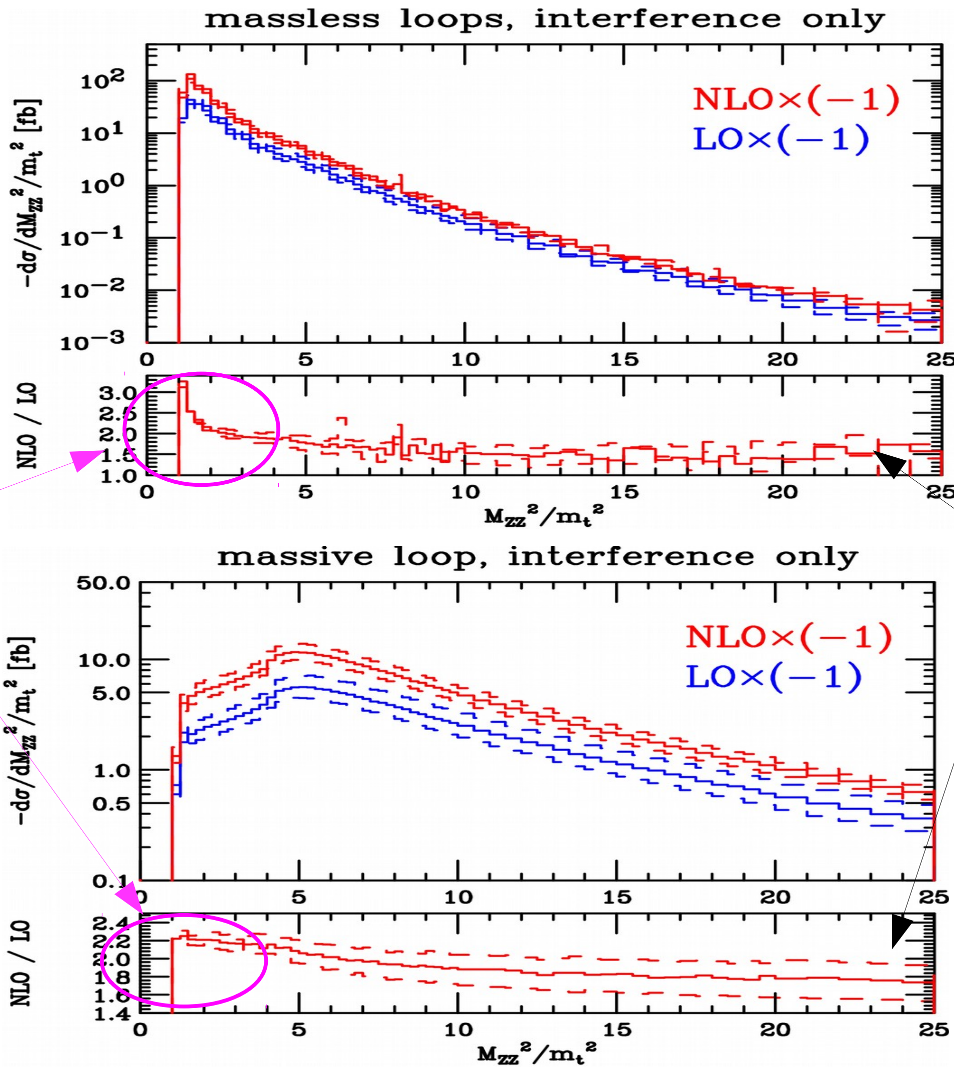
Comparison with similar work

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, hep-ph/1605.01380

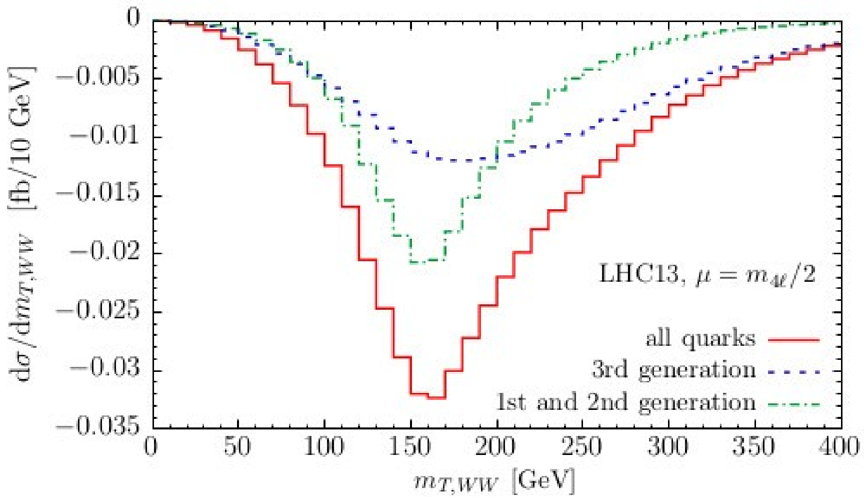


Qualitatively similar behavior of k-factors near $2m_Z$ threshold

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
- $\to$ 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

$gg \to (H) \to WW$ Results: Cross Sections

$$\sigma_{\rm LO}^{\rm signal} = 48.3^{+10.4}_{-8.4}\ {\rm fb}, \qquad \sigma_{\rm NLO}^{\rm signal} = 81.0^{+10.5}_{-8.2}\ {\rm fb}$$

$$\sigma_{\rm LO}^{\rm bkgd} = 49.0^{+12.8}_{-9.7}\ {\rm fb}, \qquad \sigma_{\rm NLO}^{\rm bkgd} = 74.7^{+5.5}_{-6.2}\ {\rm fb}$$

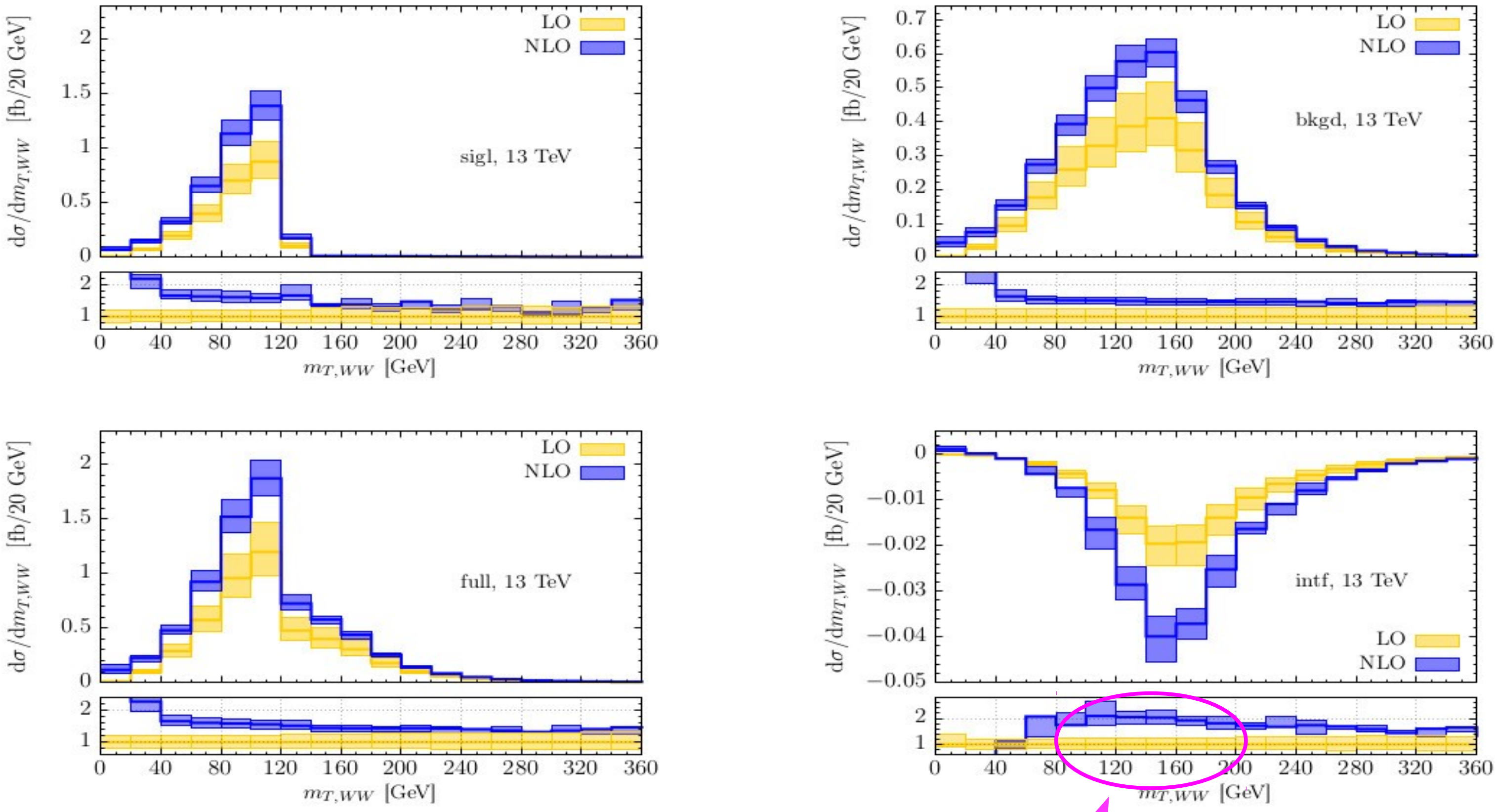
$$\sigma_{\rm LO}^{\rm intf} = -2.24^{+0.44}_{-0.59}\ {\rm fb}, \qquad \sigma_{\rm NLO}^{\rm intf} = -4.15^{+0.47}_{-0.54}\ {\rm fb}$$

$$\sigma_{\rm LO}^{\rm full} = 95.0^{+22.6}_{-17.6}\ {\rm fb}, \qquad \sigma_{\rm NLO}^{\rm full} = 151.6^{+15.4}_{-13.9}\ {\rm fb}.$$

- Destructive interference ~ **2%**
  - Higgs peak present → interference smaller than signal and background
- Scale uncertainty reduced by factor ~ 2
- $K_{\rm sigl} = 1.68 \qquad K_{\rm bkgd} = 1.53 \qquad K_{\rm intf} = 1.85$

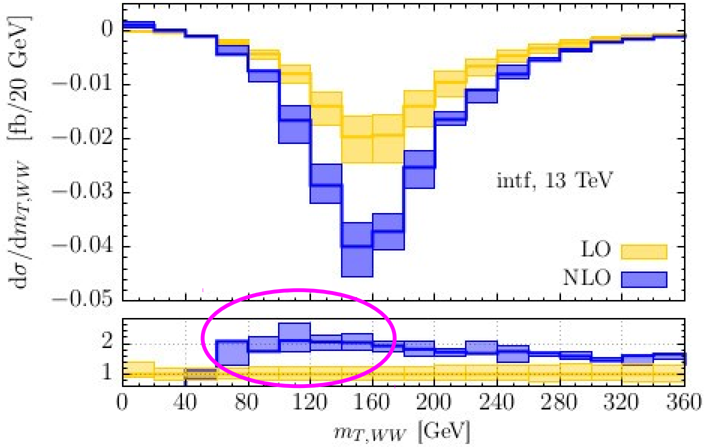
  → slightly above geometric mean

$gg \to (H) \to WW$ Results: Mass distributions



- Differential k-factors relatively flat...
- … except for interference near $2m_W$ threshold – as in ZZ case

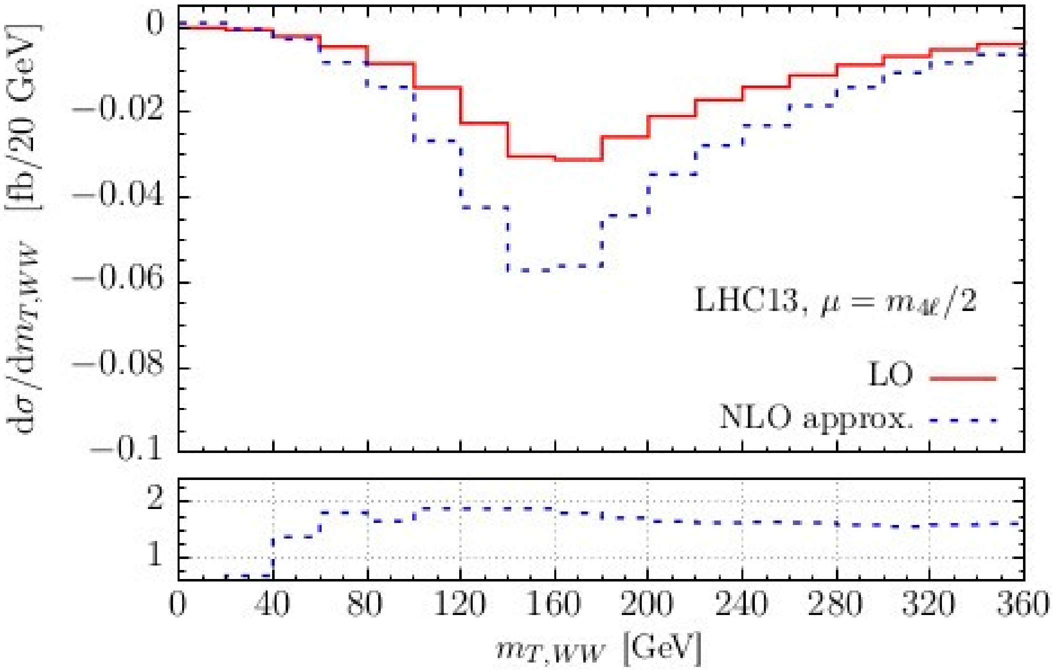
$gg \to (H) \to WW$ Results: Estimating effect of 3rd generation



- As in *ZZ* case, enhancement from massless loops
- 3rd generation loops give relatively flat differential k-factor

→ estimate by using LO results scaled by approximate k-factor

$$\sqrt{K_{\rm sigl} K_{\rm bkgd}}$$



Nice job…

Impact of NLO calculation on width constraints:

- K-factor known, can remove systemic uncertainty
- Exact impact not obvious – will wait for experimental analysis

…but is it good enough?

- NLO is known to be insufficient for onshell Higgs – **is it okay for offshell?**
  - NLO results lie **outside** LO scale uncertainty bands
  - Do we trust the **NLO scale uncertainty?**
  - **Offshell NNLO** impossible at present
  - Use NNLO results for infinite m_t to get **approximate NNLO** k-factor offshell?
- Can we understand effectiveness of Padé approximants (e.g. how well do they do for *HH* production)?

Conclusions

- Higgs off-shell behavior provides a rich environment to study Higgs physics:
  - Probe **unitaritizing behavior** of the Higgs
  - **Indirect constraint**s on Higgs width
  - **Test couplings** at high energies
- NLO corrections to interference in $gg \to ZZ$ and $gg \to WW$, are now known, at least below $2m_t$ threshold
- Difficulty of computing two-loop massive corrections

  → top mass expansion for *ZZ*

  → neglect 3rd generation for *WW*
- *ZZ* in window $150 \text{ GeV} \leq m_{4\ell} \leq 340 \text{ GeV}$
  - Moderate k-factors ~ 1.6-1.7
  - $K_{\text{intf}} \simeq \sqrt{K_{\text{sigl}} K_{\text{bkgd}}}$ **except near $2m_Z$ threshold** – driven by massless amplitudes
- *WW*:
  - Interference k-factor slightly larger than signal and background k-factors
  - Effect of 3rd generation at NLO approximated assuming uniform contribution to k-factor

THANK YOU!