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Higgs off-shell effects at NLO

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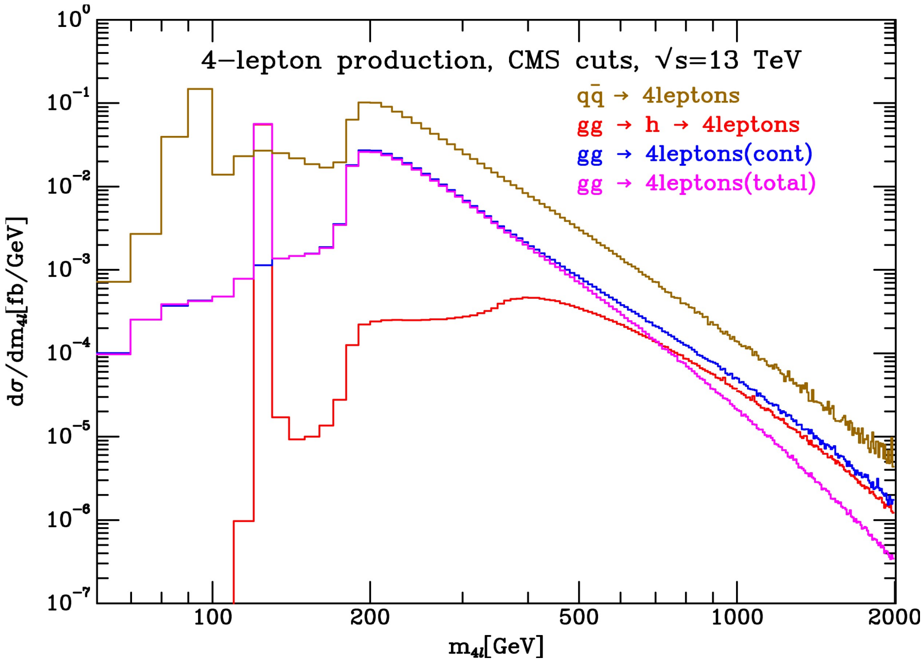
Higgs Off-shell Behavior

- Higgs properties (mass, couplings, CP state) probed using **on-shell** Higgs
- **However,** 10% of events in $H \rightarrow VV$ $(V=W,Z)$ are above $2m_V$ threshold (Kauer, Passarino '12)
- **Strong destructive interference** at high energies → probe **unitarizing behavior** of Higgs (connected to EWSB)
- Independent of Higgs width → **indirect constraint** on Higgs width (Caola, Melnikov '13)



Campbell, Ellis, Williams '13

Indirect constraints on Higgs width

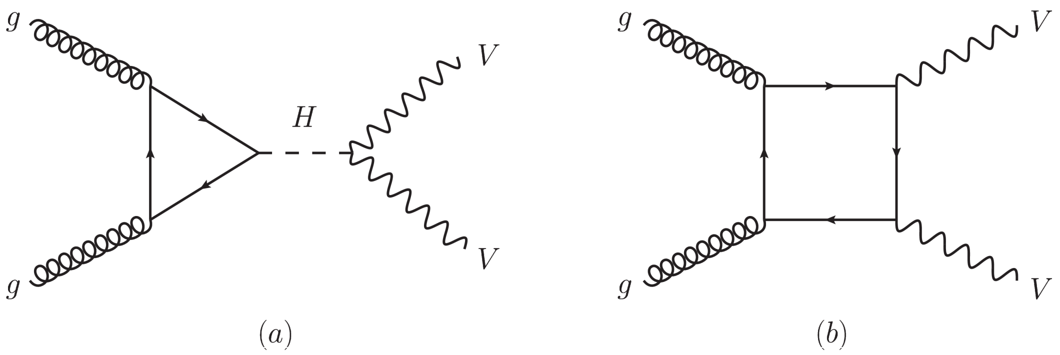
- ATLAS & CMS find $\Gamma_H < 22 - 26\ \mathrm{MeV}$
- Compared with ~ 1 GeV direct constraint
- However:
  - Model dependent:
    - Assume same couplings on-shell and off-shell
    - Can (usually) be validated
  - QCD corrections:
    - Interference effects known at **LO only** – NLO corrections **expected to be large**
    - Current approximated by known **signal** k-factors – unclear if this is justified

Englert, Spannowsky '13

Englert, Soreq, Spannowsky '14

Obtain NLO QCD corrections separately for signal, background and interference terms

Higgs Off-shell Effects at LO



“signal” “prompt / background”

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

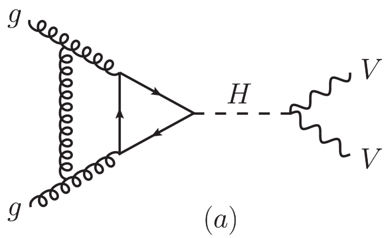
$$\to \sigma_{\mathrm{full}} = \sigma_{\mathrm{sigl}} + \sigma_{\mathrm{bkgd}} + \sigma_{\mathrm{intf}}$$

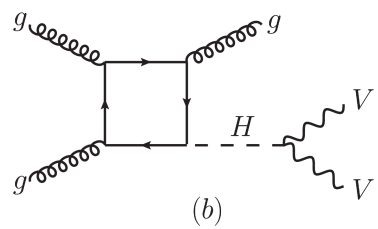
Amplitudes (incl. mass dependence) well known

Glover, v.d. Bij ‘89; Matsuura, v.d. Bij ‘91; Zecher, Matsuura, v.d. Bij ‘94; Binoth, Kauer, Mertsch’08; Campbell,Ellis, Williams ‘11, ‘14

Higgs Interference Effects at NLO

Known

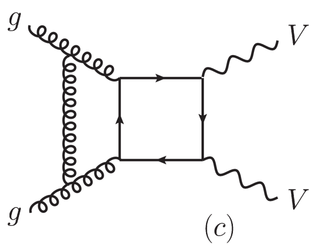


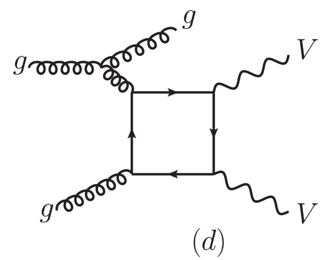


Known

Massless: known

Massive: extremely difficult / impossible

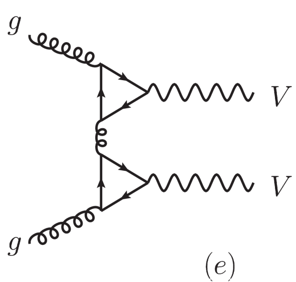


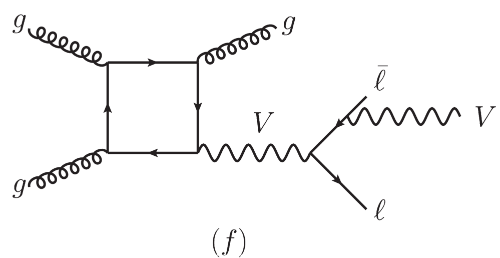


Massless: easy

Massive: moderate

Known





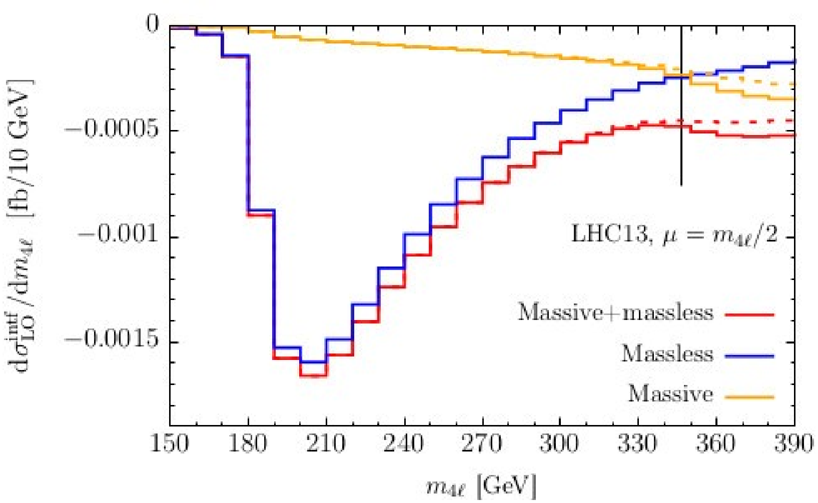
Known

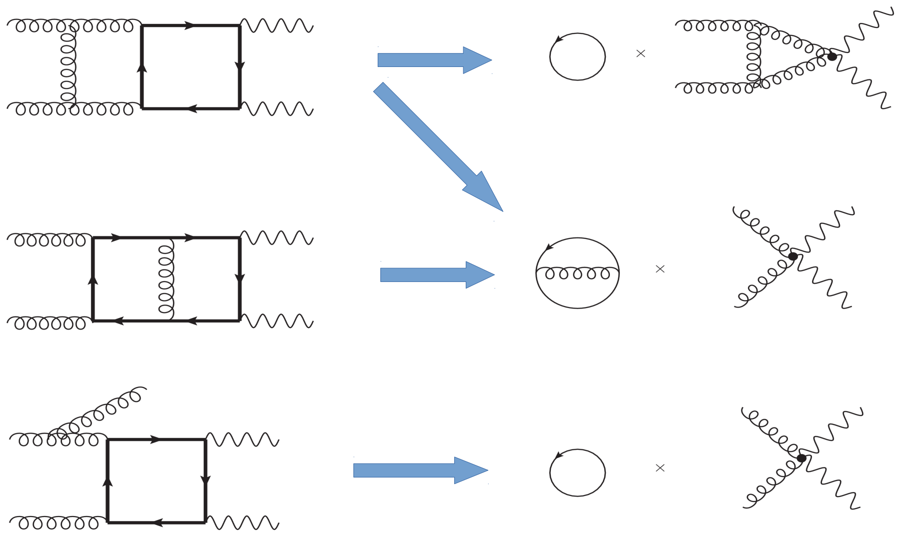
Spira, Djouadi, Graudenz, Zerwas ‘95; Harlander, Kant ’05; Aglietti, Bonciani, Degrassi, Vicini ‘07;
Ellis, Hinchliffe, Soldate, v.d. Bij ‘88;
Caola et al ‘15, v. Manteuffel, Tancredi ‘15
Hagiwara, Kuruma, Yamada ‘91; Campbell, Ellis, Zanderighi ‘07;
v.d. Bij, Glover ‘89;

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

Expand in s/m_t^2

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





- Restricted to

$m_{4\ell} \leq 2m_t$

$p_{T,j} < 150$ GeV

(Cannot probe unitarization effects)

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

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

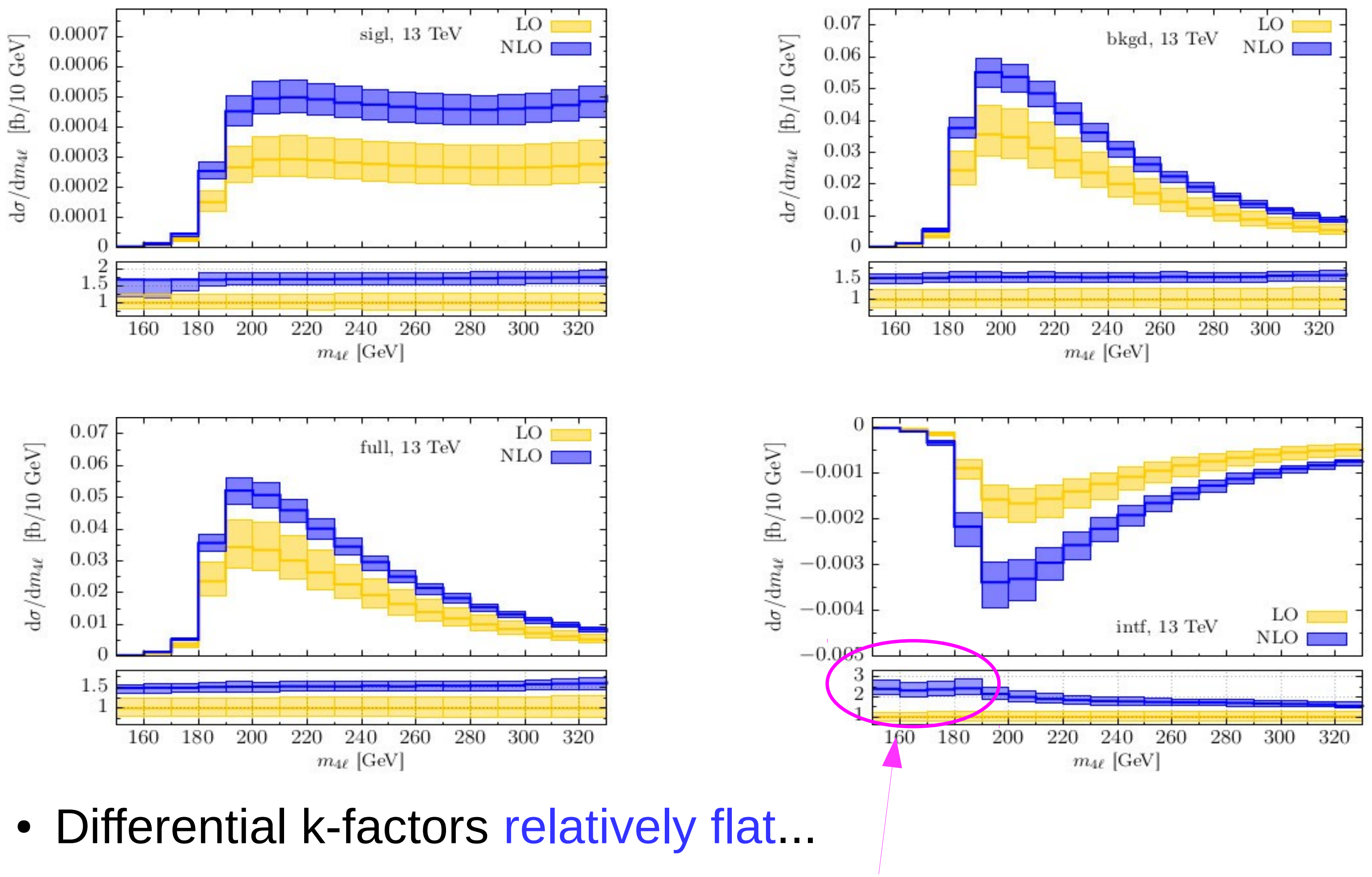
$$\sigma_{\rm LO}^{\rm bkgd} = 2.90^{+0.77}_{-0.58}\ {\rm fb}, \qquad \sigma_{\rm NLO}^{\rm bkgd} = 4.49^{+0.34}_{-0.38}\ {\rm fb}$$

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

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

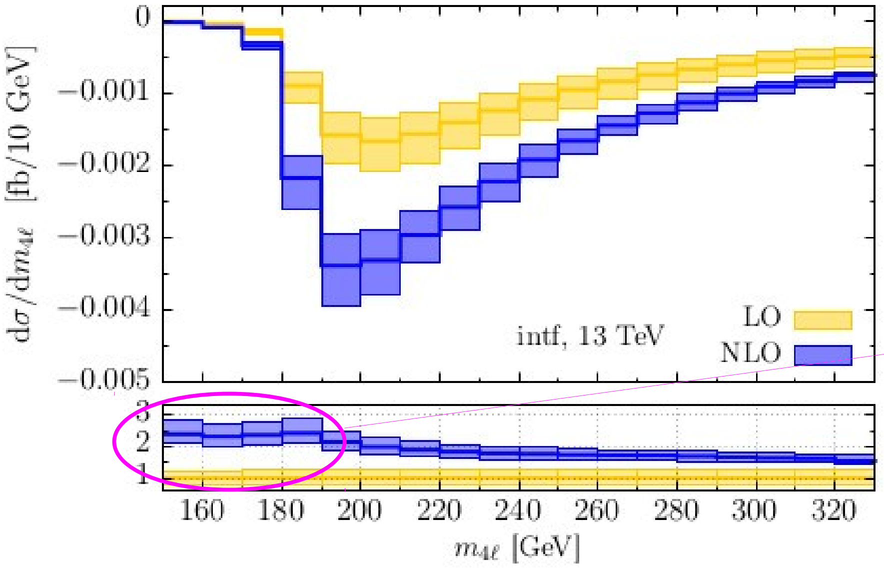
- Destructive interference ~ **5%**
  - ~ 4 x larger than signal, order of magnitude smaller than background
  - Can use specialized cuts needed to enhance relative to signal and background
- Scale uncertainty: 20%-30% at LO, 10% at NLO
- $K_{\rm sigl} = 1.72 \qquad K_{\rm bkgd} = 1.55 \qquad K_{\rm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

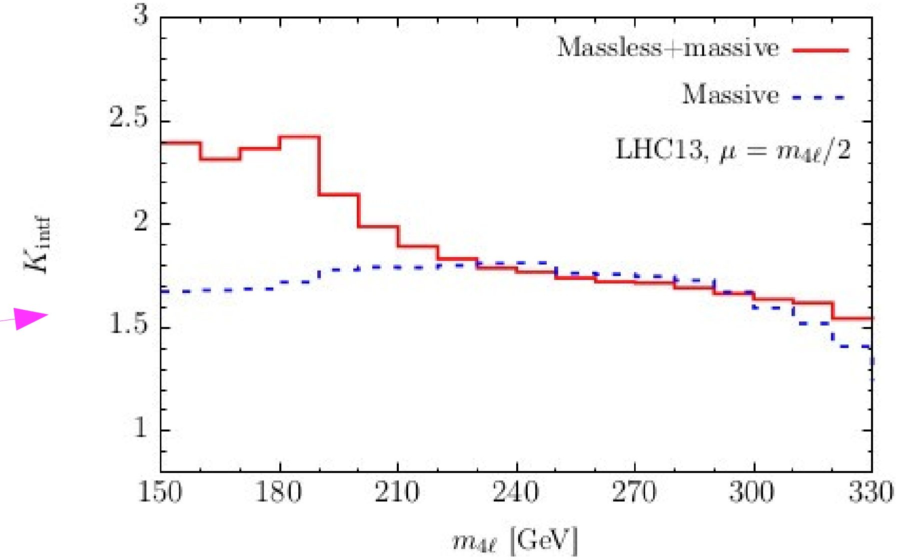
gg → (H) →ZZ Results: Mass distributions



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

gg → *(H)* → *ZZ* Results: Differential k-factor



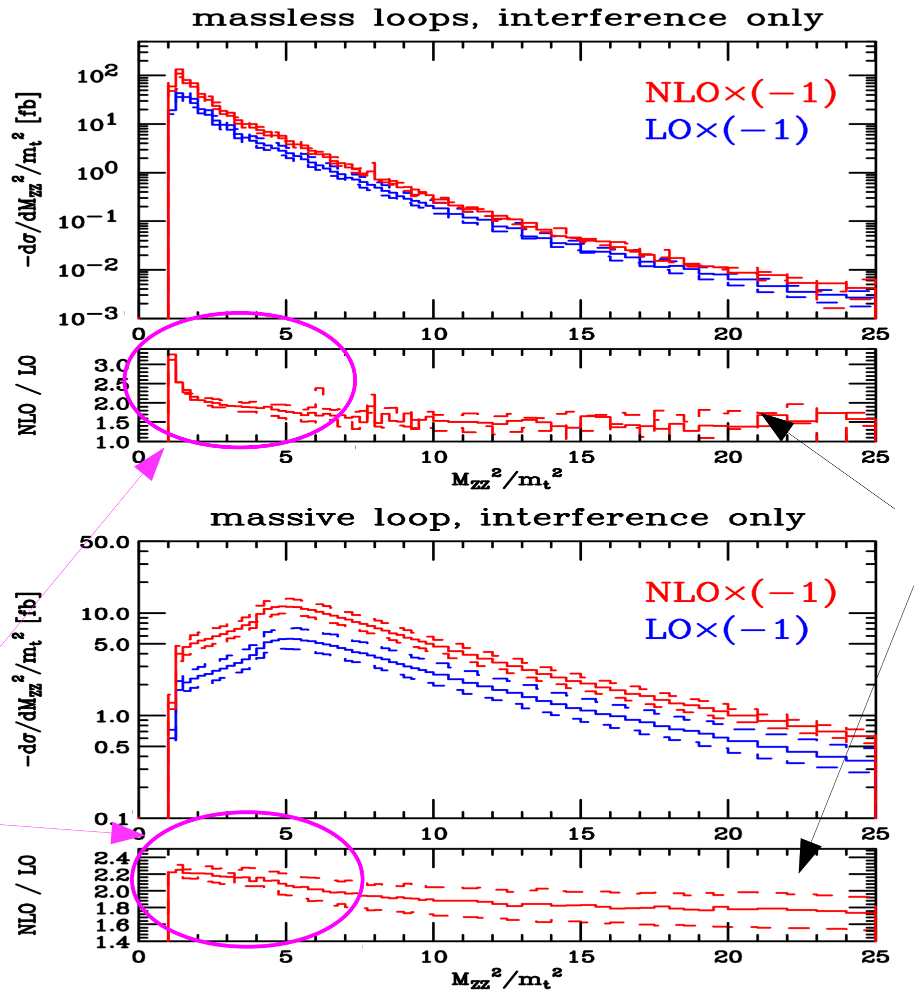


- Massless loop dominates near $2m_Z$ threshold, drives k-factor behavior

Comparison with similar work

Campbell, Czakon, Ellis, Kirchner, arXiv: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
- Results extended beyond $2m_t$ threshold using Padé approximations

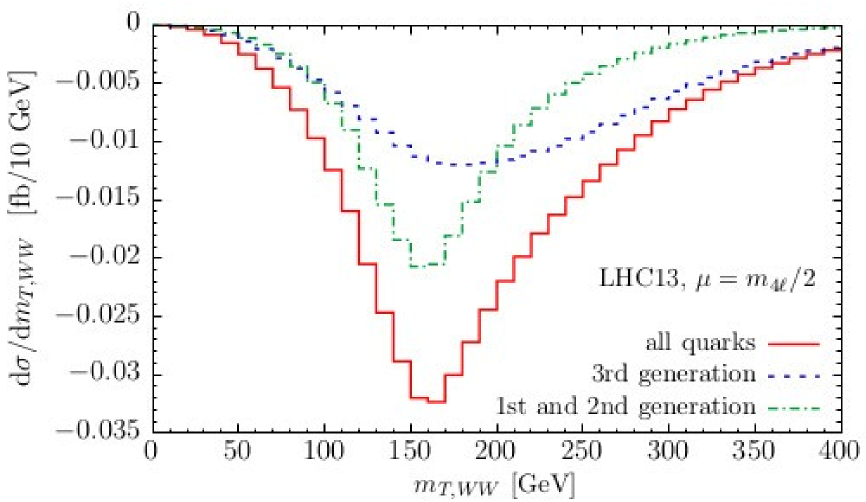


K-factor flat in high-energy tail

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

$gg \to (H) \to WW$

- Analogous to $gg \to (H) \to ZZ$
- Mass expansion more complicated since top and bottom quarks mix in loop
- → 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

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

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

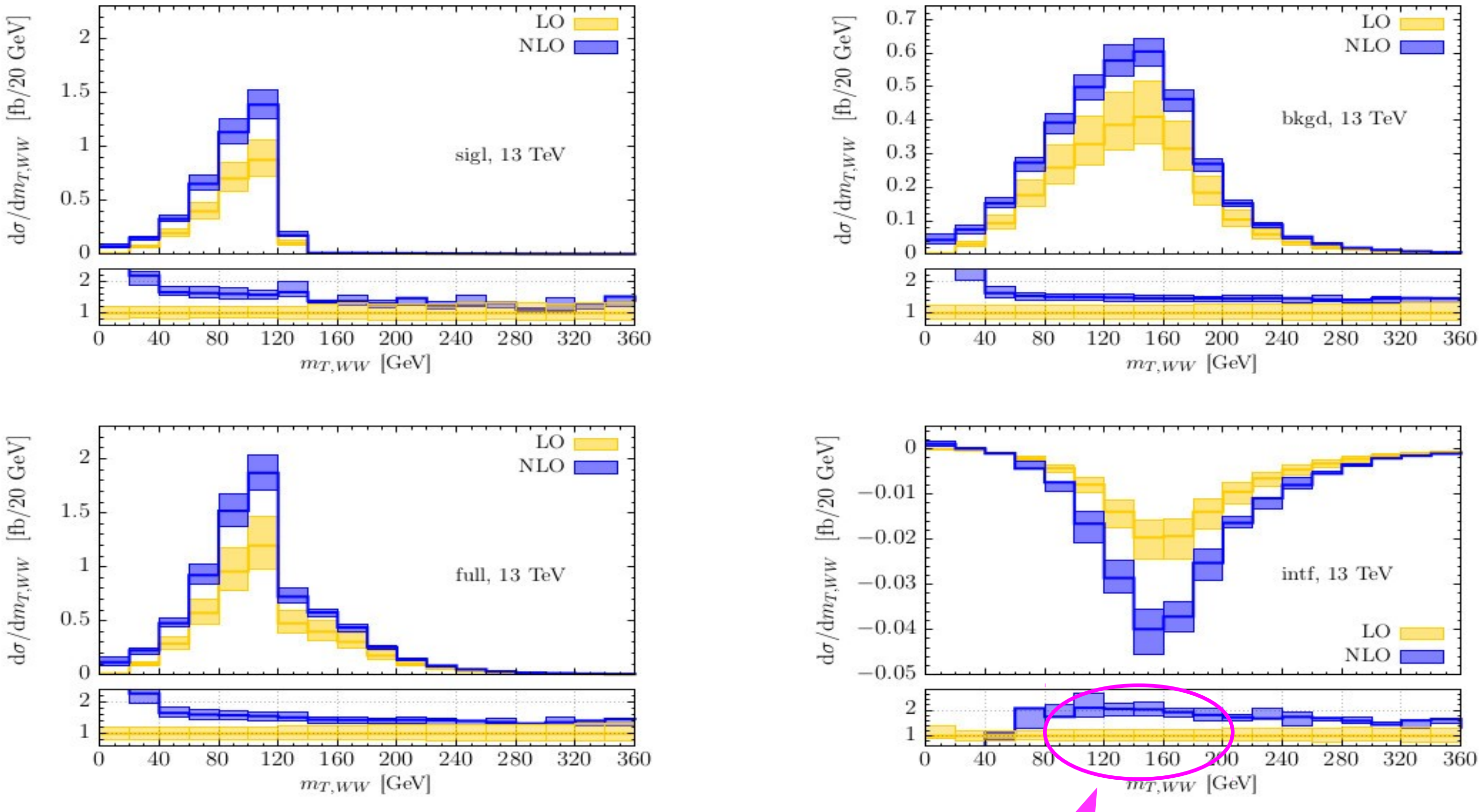
$$\sigma_{\rm LO}^{\rm intf} = -2.24^{+0.44}_{-0.59}\ {\rm fb}, \qquad \sigma_{\rm NLO}^{\rm intf} = -4.15^{+0.47}_{-0.54}\ {\rm fb}$$

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

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

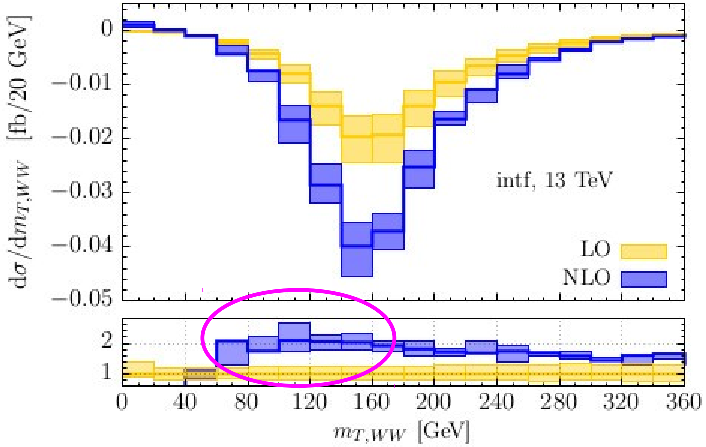
→ fairly close to geometric mean

gg → *(H)* → *WW* Results: Mass distributions



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

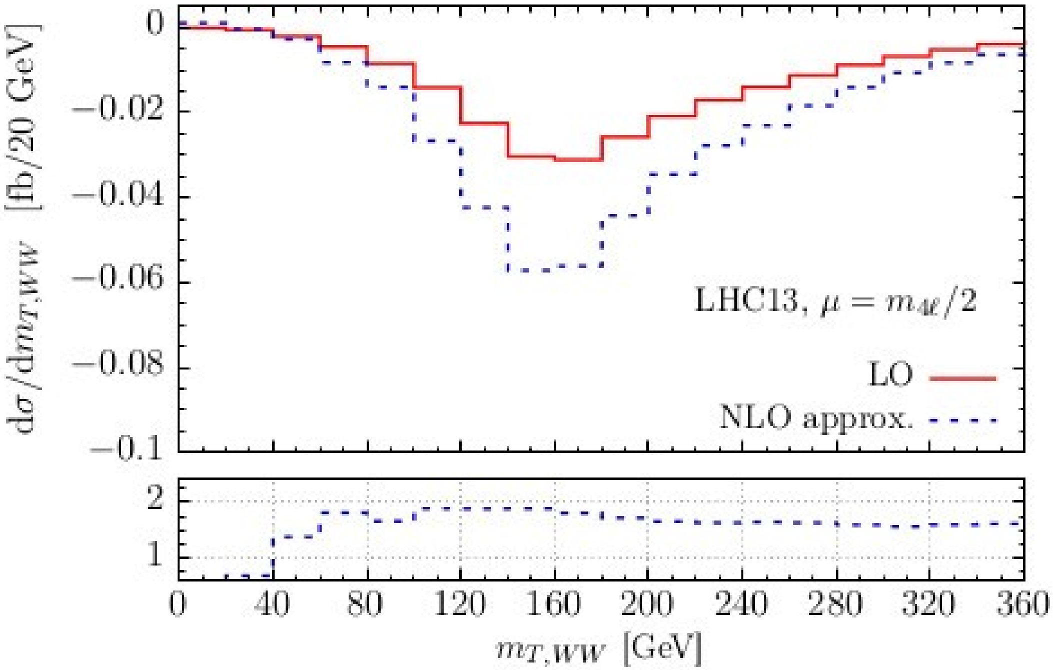
$gg \to (H) \to WW$ Results: Estimating effect of 3rd generation



- 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

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



Conclusions

- Computed NLO corrections to *gg* → *ZZ* and *gg* → *WW*, focusing on off-shell Higgs interference effects
- Difficulty of computing two-loop massive corrections

  → top mass expansion for *ZZ*

  → neglect 3rd generation for *WW*
- *ZZ* in window $150\ \mathrm{GeV} \leq m_{4\ell} \leq 340\ \mathrm{GeV}$
  - Moderate k-factors ~ 1.6-1.7
  - $K_{\mathrm{intf}} \simeq \sqrt{K_{\mathrm{sigl}} K_{\mathrm{bkgd}}}$ **except near *2m* 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!