Vector boson pair production in gluon fusion including interference effects with off-shell Higgs at the LHC

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Based on collaboration with *F. Caola*, *M. Dowling, K. Melnikov*, *R. Röntsch*
arXiv:1605.04610

Introduction and motivation

Vector boson pair production provides many observables
for precision LHC phenomenology

On-shell Production

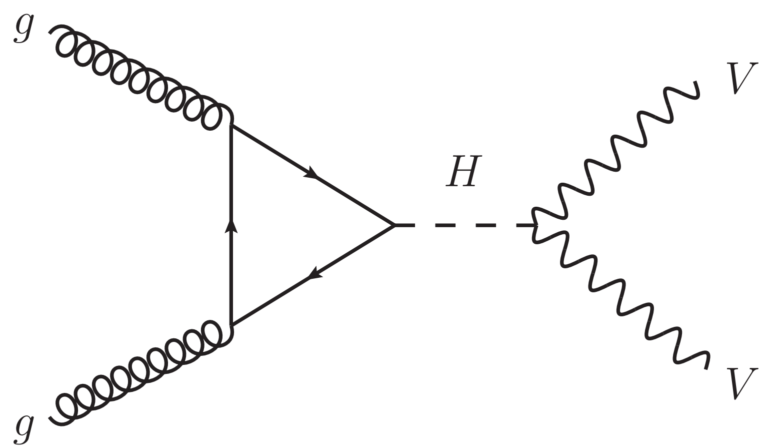
- ✓ Study EW Symmetry Breaking mechanism
- ✓ Anomalous gauge couplings?

Off-shell Production

- ✓ Background for Higgs discovery
- ✓ Crucial to study its properties: *Couplings*, **width**

Facts on Higgs off-shell behaviour

Higgs produced in **gluon fusion**, decays into **vector bosons**



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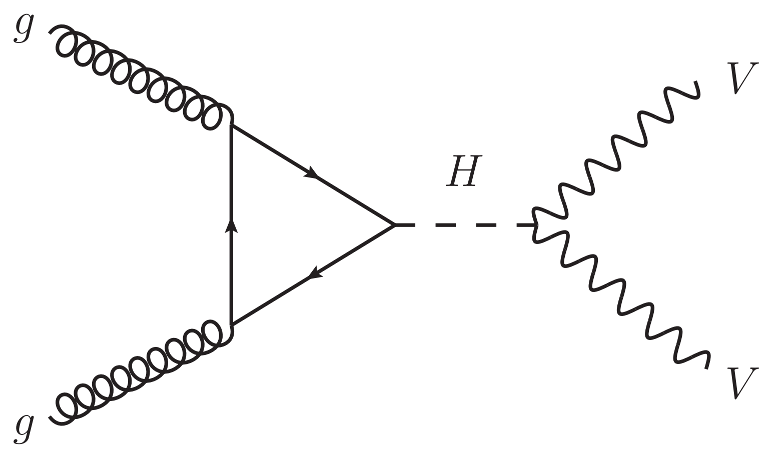

- Higgs properties probed using **on-shell Higgs** *(mass, couplings, CP state)*
- **BUT** - **10% events** $H \to VV$ are **above** $2M_V$ **threshold** [Kauer, Passarino '12]
- At high energies **strong destructive interference** *(unitarization)*
- Independent of width, **strong constraints** on **Higgs width** [Caola, Melnikov '13]

Constraints on Higgs width

- Direct constraints limited by ***experimental resolution*** $\approx$ **1GeV**
- **Indirect constraints** studying off-shell **Higgs** production in **VV**

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H} \qquad\qquad \sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}.$$

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ATLAS & CMS find $\boldsymbol{\Gamma_H < 22 - 26}$ **MeV** !

Compared to SM prediction $\approx$ 4 MeV

Constraints are **model dependent**

- Couplings must *remain unchanged* at *high energies*!
- Can be *validated*

[Englert, Spannowsky ‘13; Englert, Soreq, Spannowsky ‘14]

Higgs signal $gg \rightarrow H \rightarrow VV$ and *interference* with prompt ampl.
scale differently at high energies

Therefore it is crucial to have **NLO QCD** corrections separately for **signal**, **background** and **interference terms**!

Theory predictions for VV production

- $q\bar{q}$ channel completely known **@ NNLO**
  [Cascioli et al ‘13; Gehrmann et al ‘14; Grazzini et al ‘15; Grazzini et al ‘16]

- gg channel *(background)* **@ NLO** for **on-shell** ZZ and WW
  [Caola, Melnikov, Röntsch, **LT** ‘15; Caola, Melnikov, Röntsch, **LT** ‘16]

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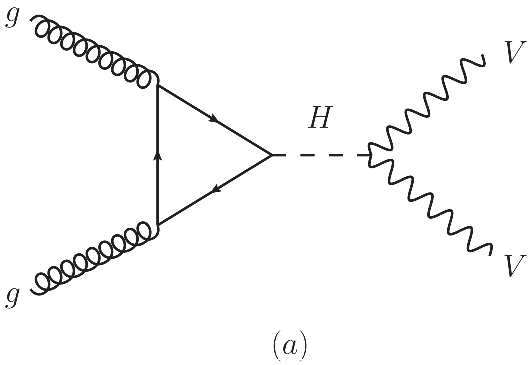
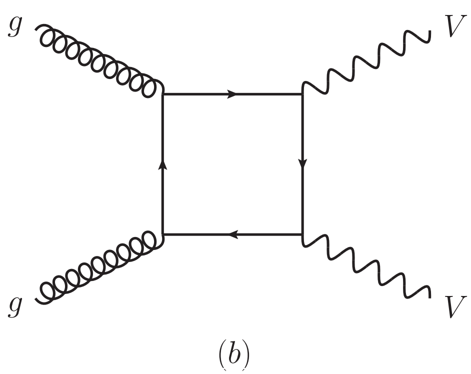
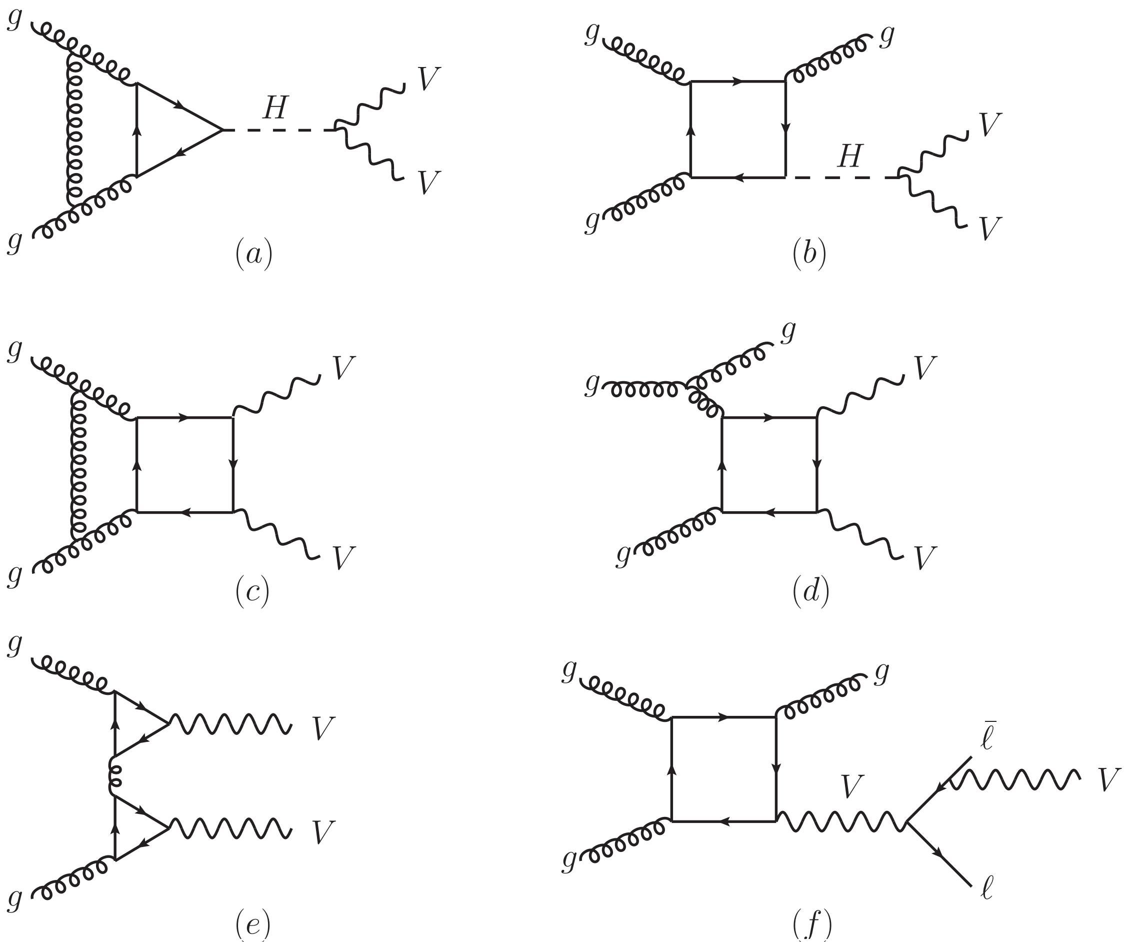
Signal – Background **interference** was known only **@ LO**
[Glover, Bij ‘89; Matsuura, Bij ‘91; Zecher, Matsuura, Bji ‘94; Binoth, Kauer, Mertsch ‘08; Campbell, Ellis, Williams ’11, ‘14]





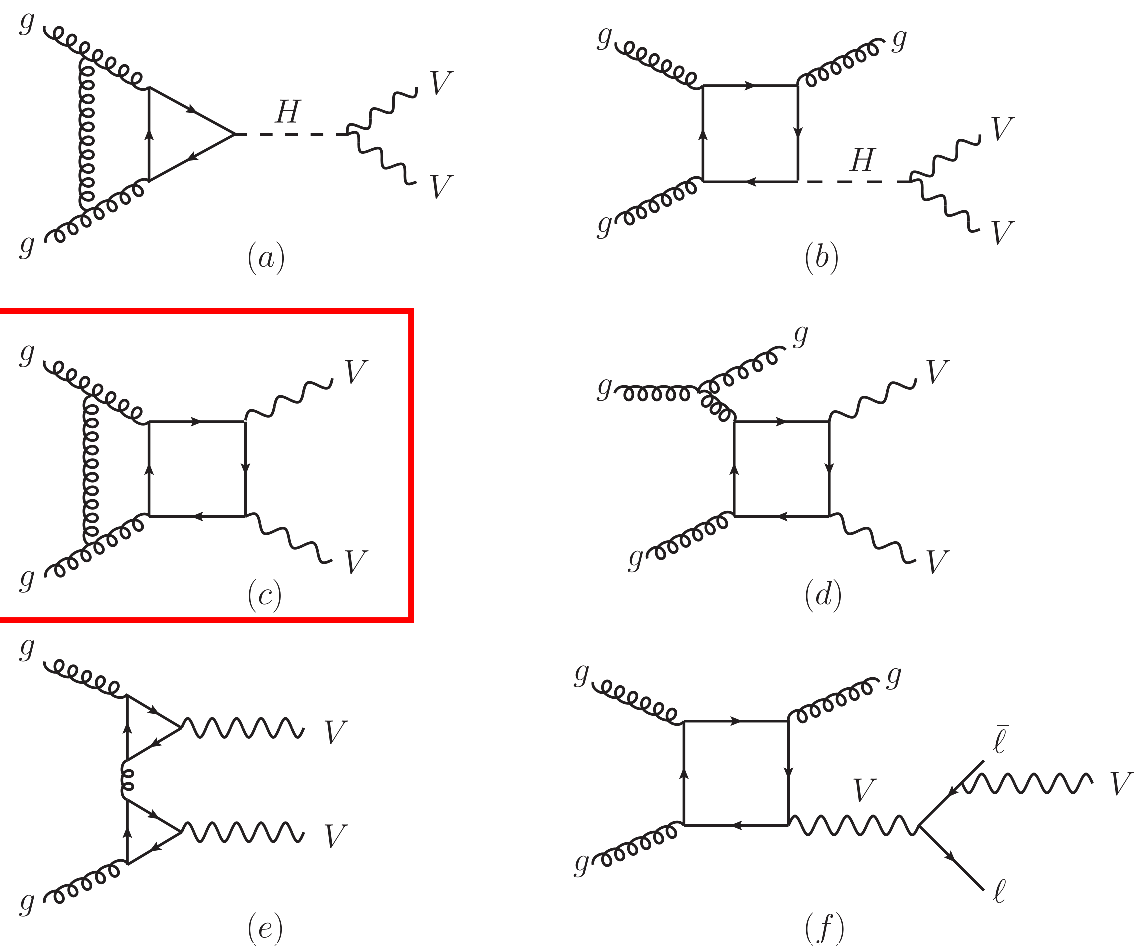
What do we need - Interference @ NLO



What do we need - Interference @ NLO

Bottleneck

- ✓ Known @ 2-loops in **massless** limit [Caola et al. ‘15; von Manteuffel, **LT** ‘15]
- ✓ Exact m_t dependence still **out-of-reach**
- ✓ Numerical methods? (**HH @ NLO**) [Borowka et al. ‘16; Borowka et al. ‘16]



Top-mass dependence is **crucial** at high **energies** / high $\boldsymbol{p_T}$

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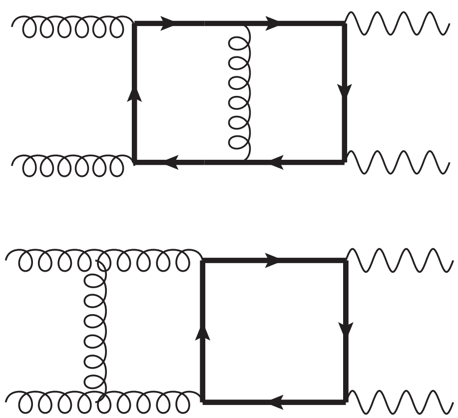
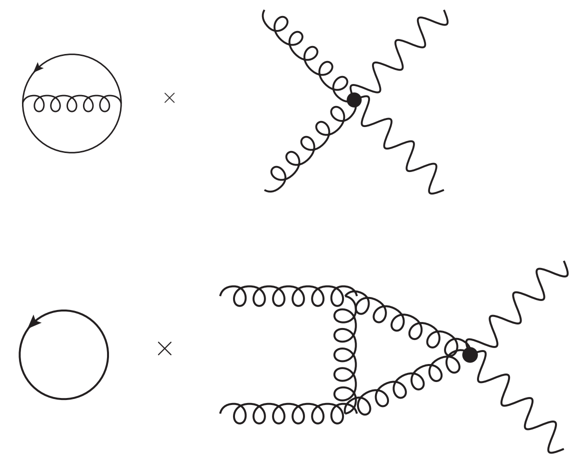
Attempt Top-mass expansion – $s \ll {m_t}^2$

Expansion trivializes two-loop amplitudes !



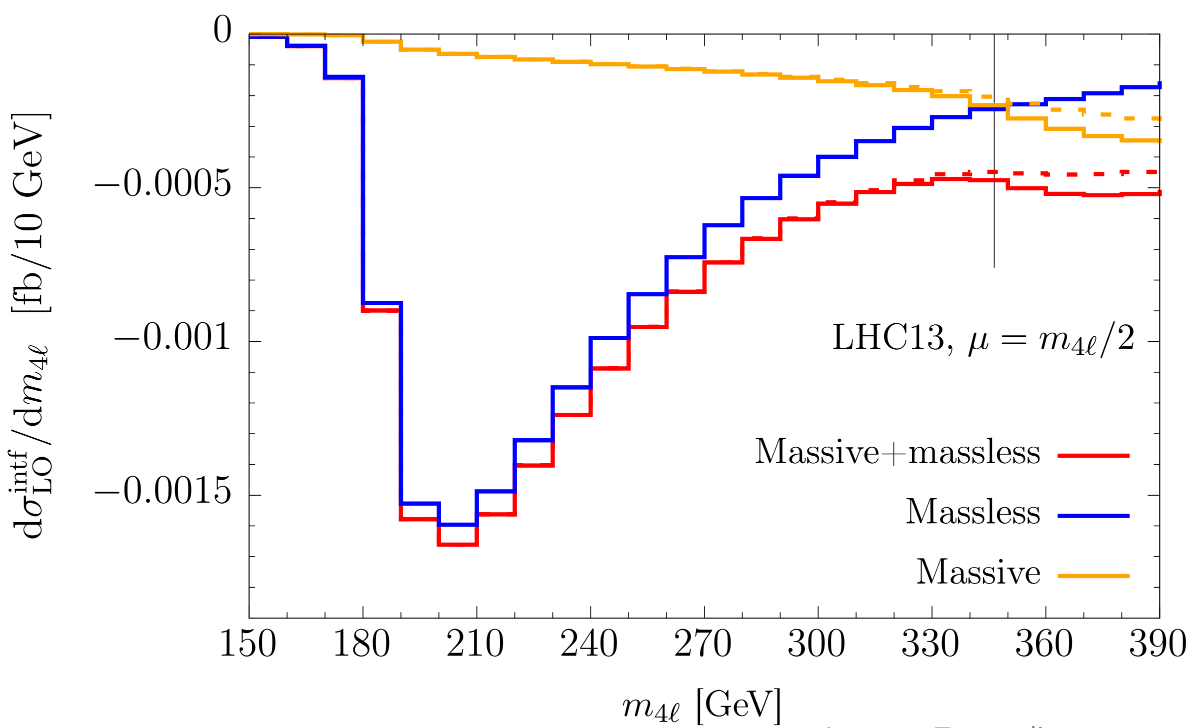
$m_t \rightarrow \infty$



Simple to implement for $gg \rightarrow ZZ$, **less trivial** for $gg \rightarrow WW$

Top-mass dependence is **crucial** at high **energies** / high $\boldsymbol{p_T}$

Possibly valid for partonic energies $s \lesssim 4m_t^2$
Expanding up to $(s/m_t^2)^4$ we see



$gg \to (H) \to ZZ \to 4l$
LO Signal/bkg *interference*

Solid line: exact in m_t
Dashed line: expansion in $1/m_t$

Vertical line → $2m_t$ threshold

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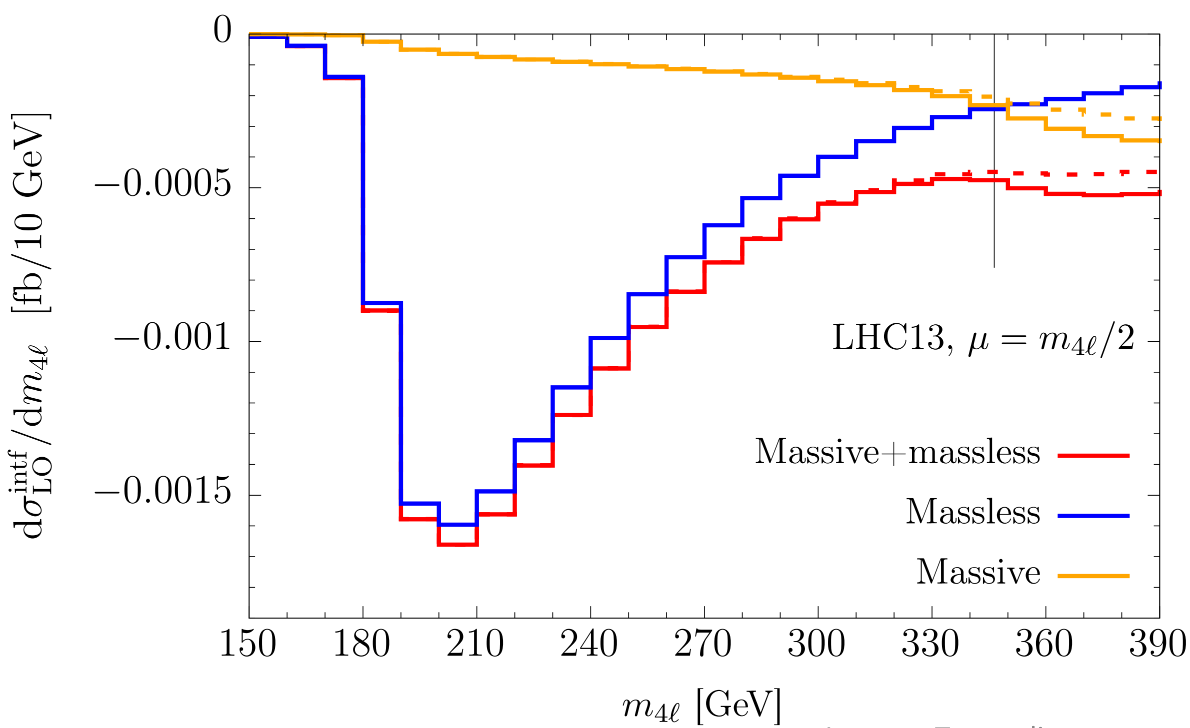

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Vertical line → $2m_t$ threshold

Restrictions:
$m_{4l} \leq 2m_t$
$p_{Tj} < 150$ GeV

Phenomenology studies for $gg \to (H) \to ZZ \to 4l$

- *Virtual* and *real* amplitudes for **background** expanded to $(s/m_t^2)^4$

- $gg \to ZZ \to 4l$ @ 13 TeV LHC
- **Dynamical scale** $\mu_F = \mu_R = \{\frac{m_{4l}}{4}; \frac{m_{4l}}{2}; m_{4l}\}$
- Impose **minimal cuts**:

  - *150 GeV* $\leq m_{4l} \leq$ *340 GeV*

  - $p_{Tj} < 150$ *GeV*

  - *60 GeV* $\leq m_{ll} \leq$ *120 GeV*

Expect **large radiative corrections**

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Expect **large radiative corrections**

We find a **K-factor** of $\sim$1.53

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

Different contributions in detail

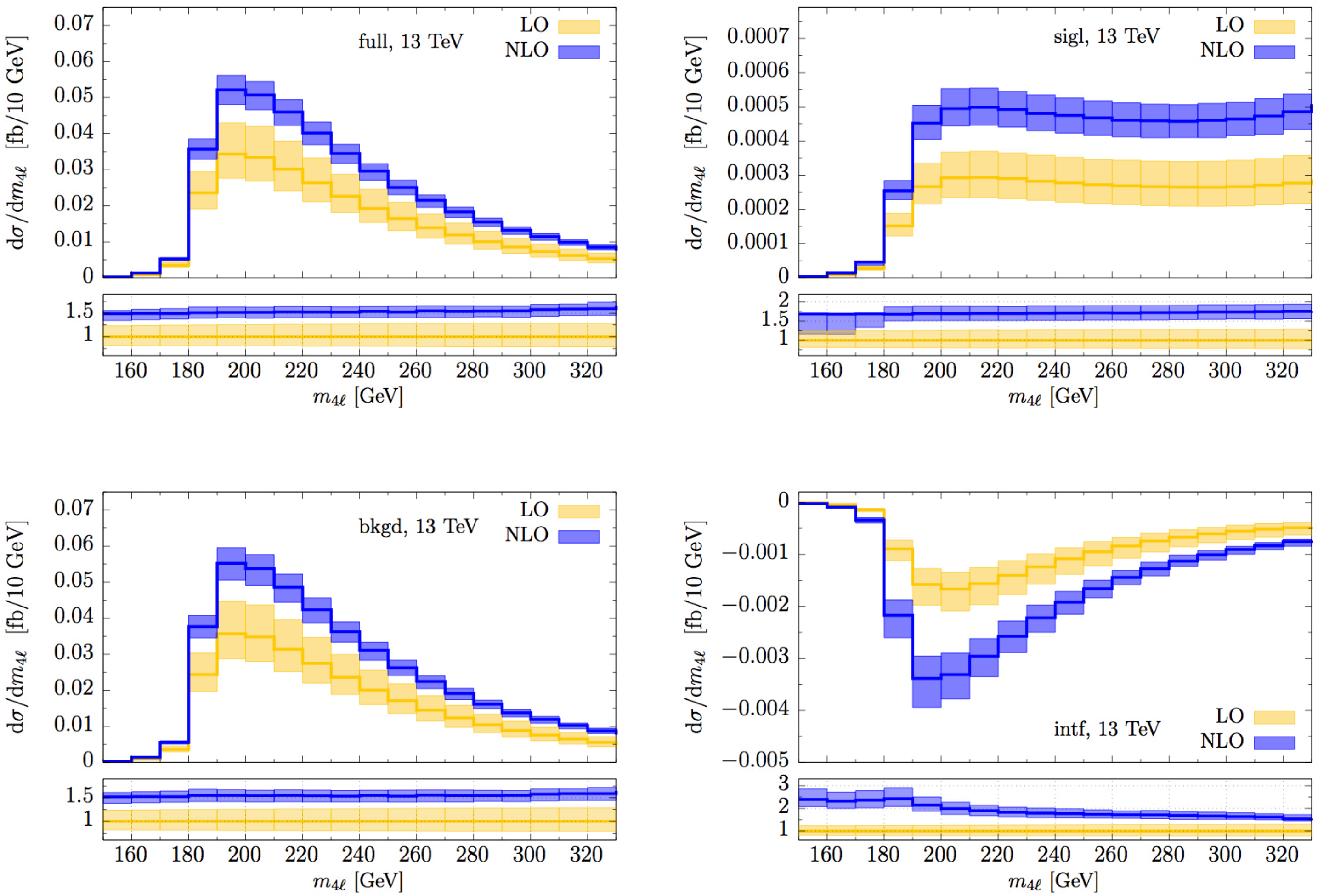
$$\sigma_{\rm LO}^{\rm signal} = 0.043^{+0.012}_{-0.009}\ {\rm fb}, \qquad \sigma_{\rm NLO}^{\rm signal} = 0.074^{+0.008}_{-0.008}\ {\rm fb}$$

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

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

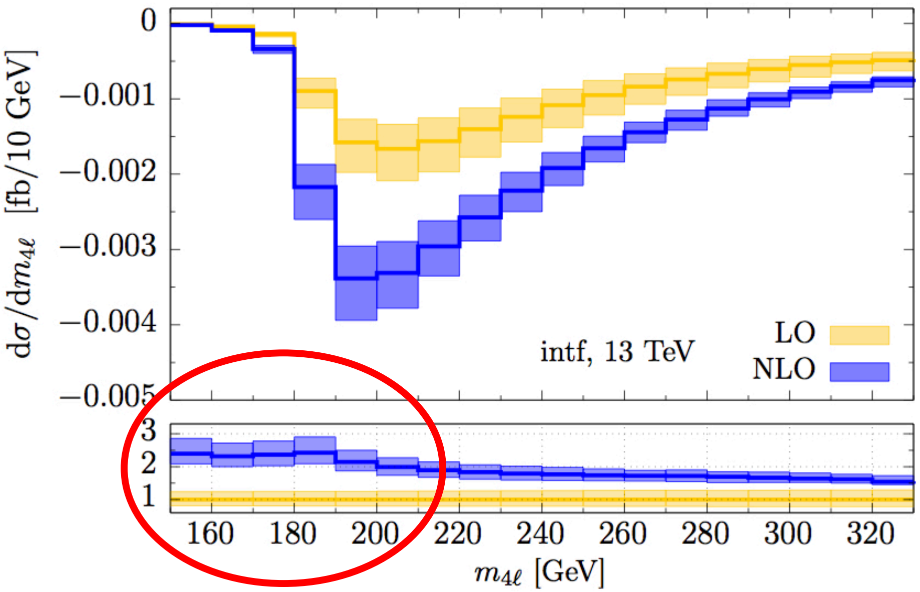
1. Destructive interference $\sim 5\%$ of background
2. Interference is 4 times larger than *signal*
   Use specialized cuts to enhance it
3. *Scale uncertainty* $\sim 20-30\%$ @ LO → **10% @ NLO**
4. *K-factors*:
   $K_{sigl} = 1.72\,; \quad K_{bkgd} = 1.55\,; \quad K_{intf} = 1.65 \;\approx\; \sqrt{K_{sigl}K_{bkgd}}$

m_{4l} distributions



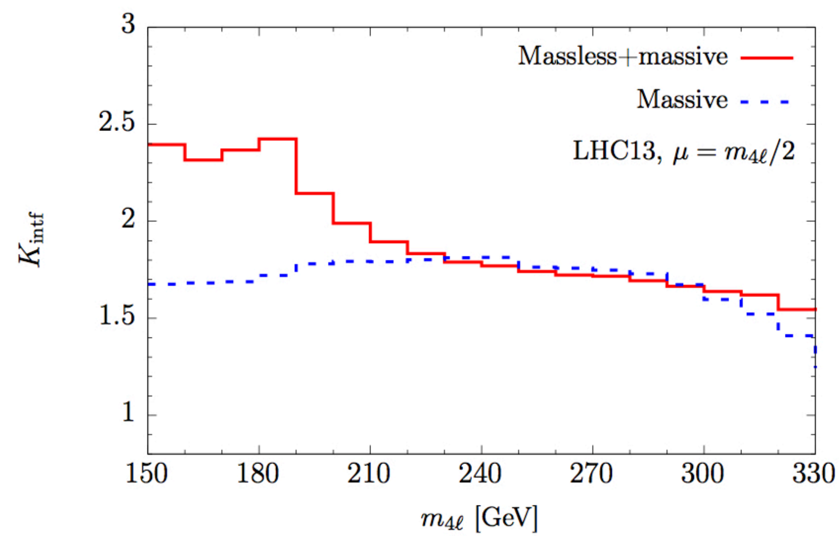
K-factors flat except for interference near $2m_Z$ threshold

K-factor of the interference



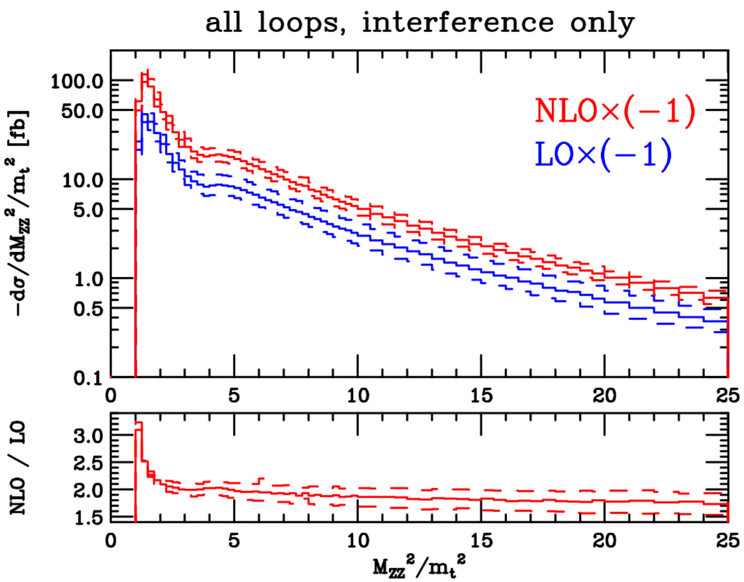
Massless loop dominates near $2m_Z$

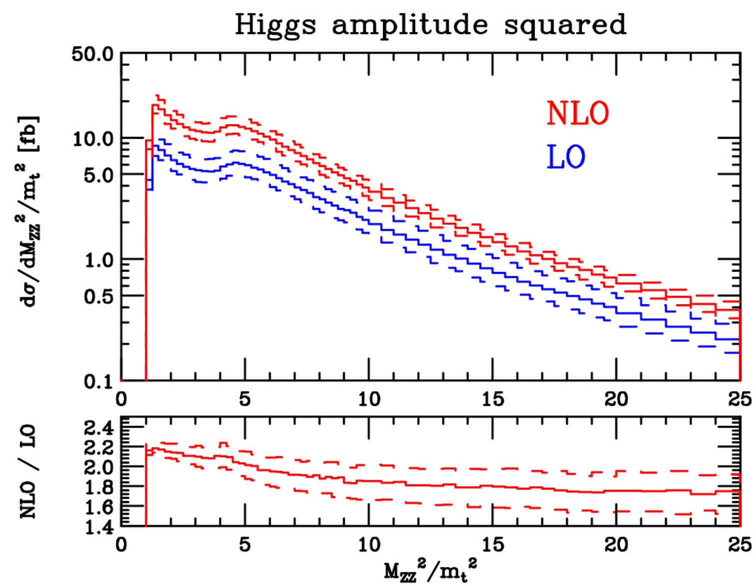
It <u>drives the k-factor behaviour</u>



Similar findings in [arXiv:1605.01380]

Campbell, Czakon, Ellis, Kirchner





Set-up:

1. They consider only interference
2. On-shell Z bosons, $m_{ZZ} > 2\, m_Z$
3. Expansion two-loop to $\left(\frac{s}{m_t^2}\right)^6$
4. Real emission exact in m_t

5. **Padé approximation** to extend results beyond $2m_t$ threshold

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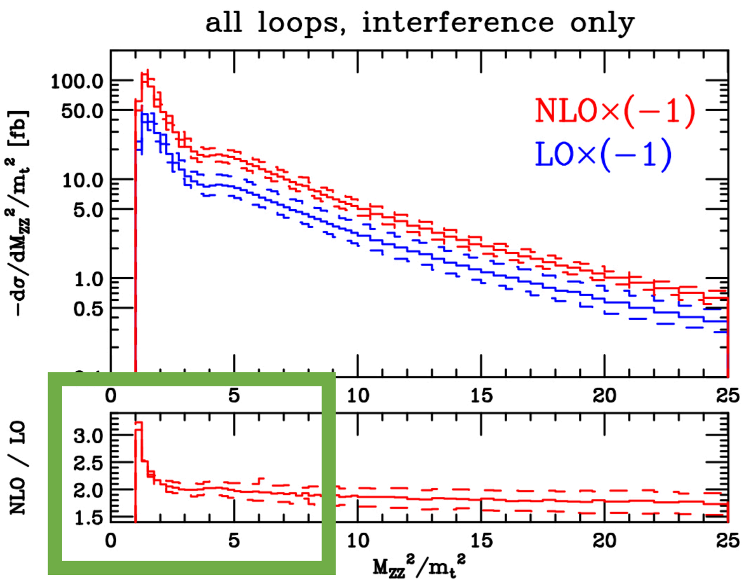

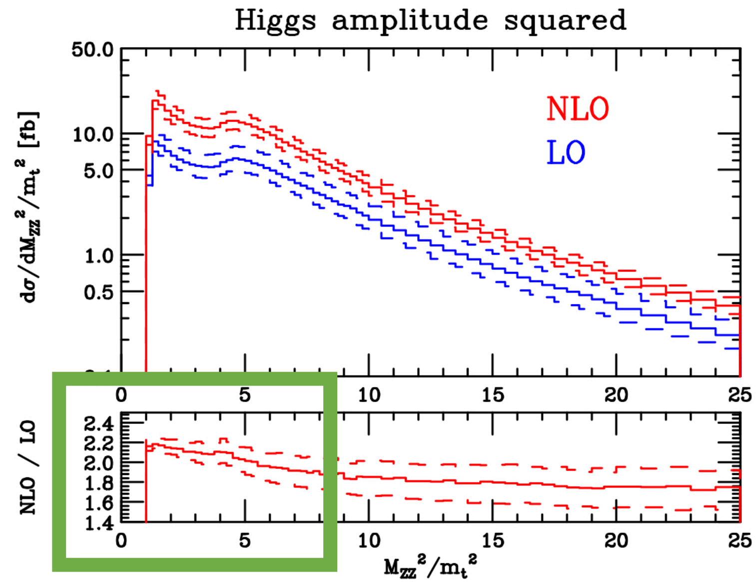

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5. **Padé approximation** to extend results beyond $2m_t$ threshold

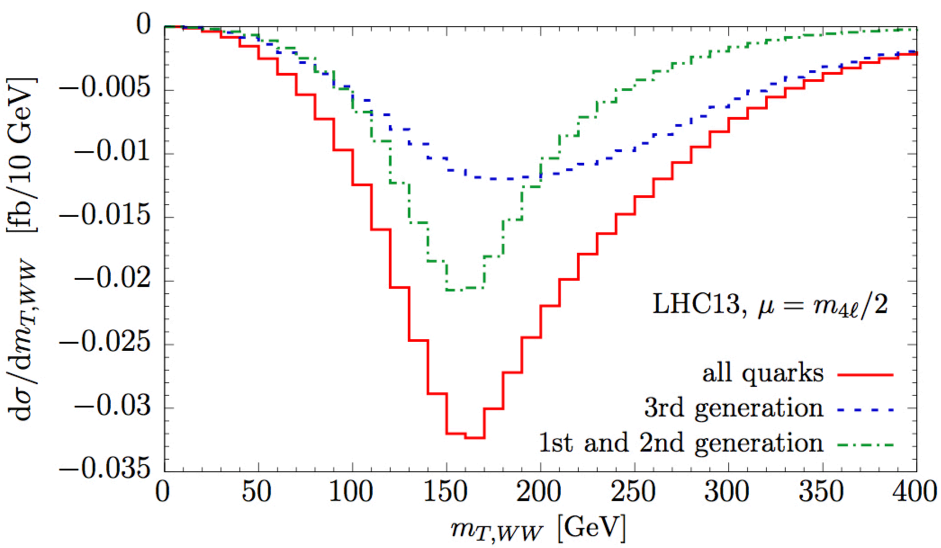
Qualitatively similar behaviour of k-factors near the $2m_Z$ threshold !

Phenomenology studies for $gg \to (H) \to WW \to 4l$

- *Mass expansion non-trivial* → top and bottoms mix in the loops!

  - Neglect entirely 3rd generation in first approximation

$$m_{\mathrm{T,WW}} = \sqrt{2E_{\perp,\mathrm{miss}}\, p_{\mathrm{T},\ell\ell}(1-\cos\tilde{\phi})}$$



Assess 3rd gen. importance @LO

- For $m_{T,WW} < 200$ GeV comparable to massless !
- Dominating for high $m_{T,WW}$!

Necessarily PARTIAL results

Phenomenology studies for $gg \to (H) \to WW \to 4l$

- $gg \to (H) \to WW \to \nu_e \, e^+ \, \mu^- \bar{\nu}_\mu$
- No kinematic cuts imposed (*no need to restrict* $p_{T\,j}$ *here*!)

  - We want to be *fully inclusive* → cuts can be easily accommodated !
- *Same scales* as for ZZ

Necessarily **PARTIAL** results

At least *partial information* on radiative effects in WW → Large K-factors 1.59

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

Different contributions in detail

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

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

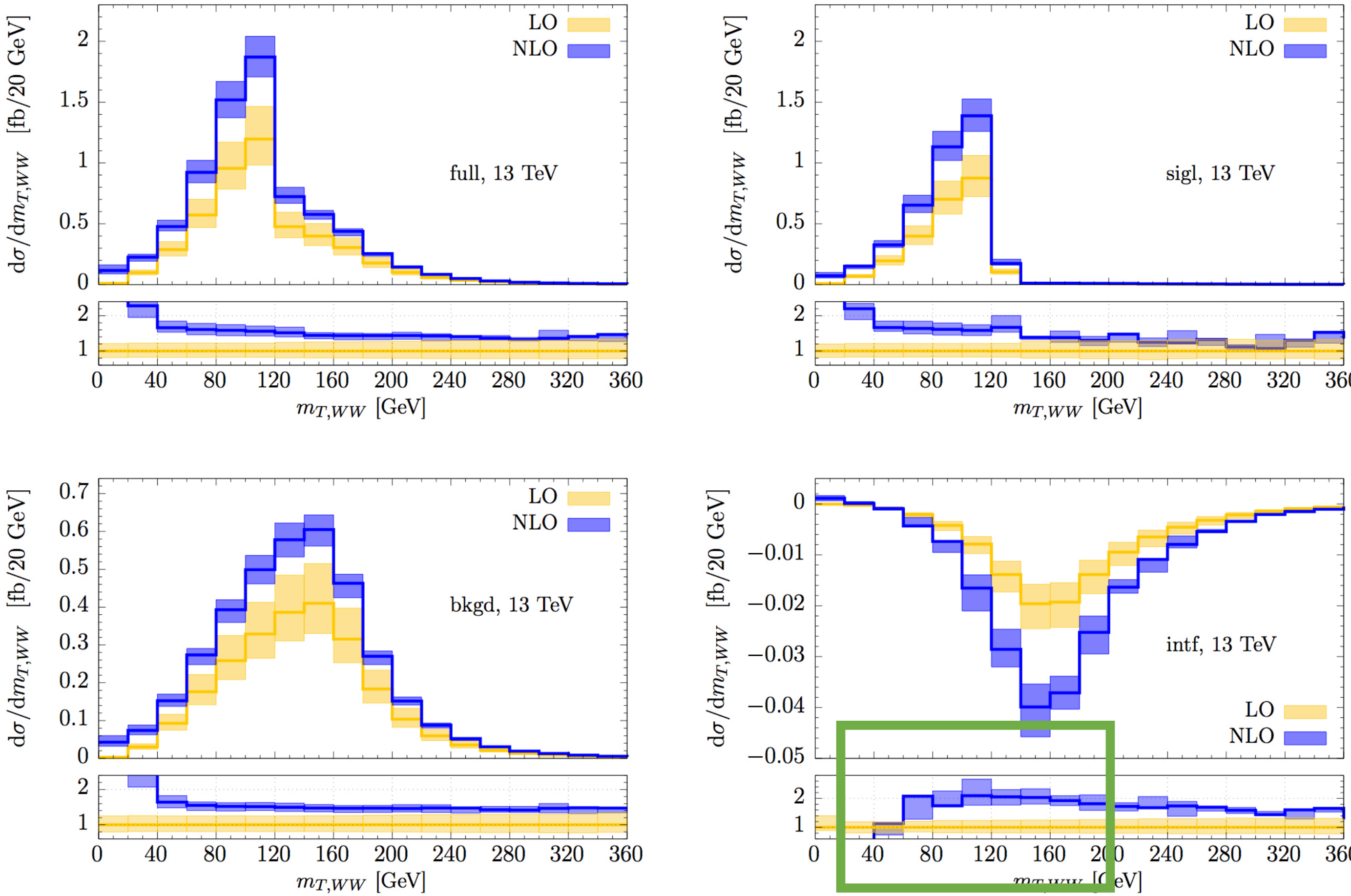
$$\sigma_{\rm LO}^{\rm intf} = -2.24^{+0.44}_{-0.59}\ {\rm fb}, \qquad \sigma_{\rm NLO}^{\rm intf} = -4.15^{+0.47}_{-0.54}\ {\rm fb}$$

1. Destructive interference $\sim$2% of background
2. Interference smaller than signal, we can see the Higgs peak!
3. *Scale uncertainty* reduced of a factor 2

4. *K-factors*:

   $K_{sigl} = 1.68$; $K_{bkgd} = 1.53$; $K_{intf} = 1.85 \neq \sqrt{K_{sigl}K_{bkgd}}$

$m_{T,WW}$ distributions

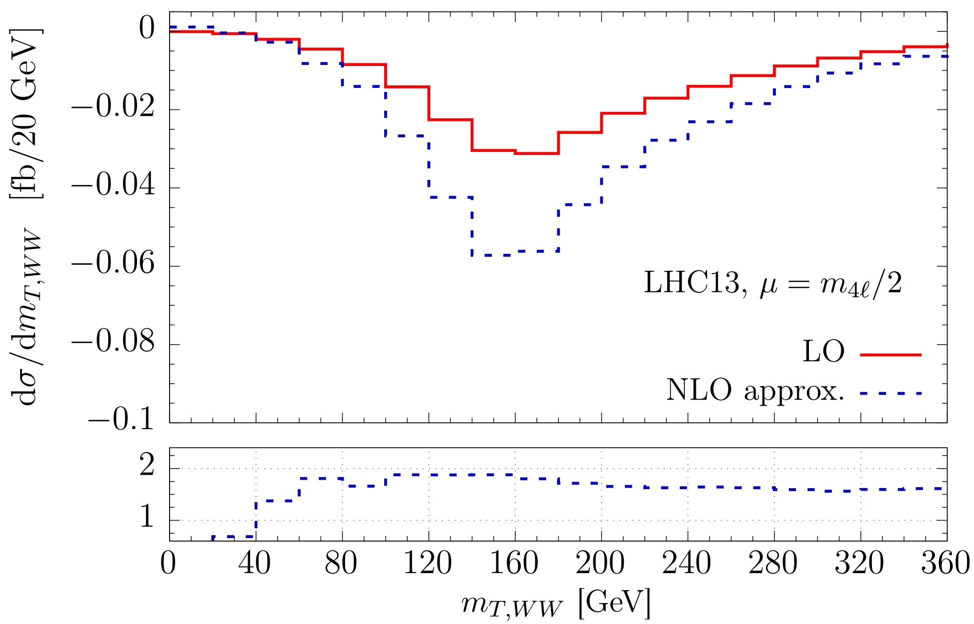


Same K-factor pattern @ $2m_{WW}$

Can we estimate impact of 3rd generation?

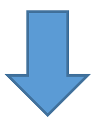
K-factor *interference* from massive loops relatively flat in the ZZ case

$\boldsymbol{m_{T,WW}}$ distribution for intf. In ggWW @ 13 TeV



Estimate effect of 3rd generation by rescaling LO with approximate K-factor

$$K \sim \sqrt{K_{sigl} K_{bkgd}} \sim 1.60$$



Very *simple-minded* approximation based on behaviour of ZZ massive K-factors!

Conclusions

- We computed $gg \to ZZ$ and $gg \to WW$ focusing on off-shell Higgs *interference* effects
- Account of top-mass effects *approximatively* for $gg \to ZZ$

↓

Window $150\ GeV < m_{4l} < 340\ GeV$ where we can claim to have full control on *mass effects*!

Moderate K-factor ~ 1.6 - 1.7, flat except close $2m_Z$ threshold

- WW → only approx. 3rd gen. estimate with flat K-factor
- Massless interference larger K-factor than sigl. and bkgd.

Thanks !