NLO Corrections to VV production through gluon fusion

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hep-ph/1509.06734, hep-ph/1511.0861
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Diboson production

Why study pp → VV ?

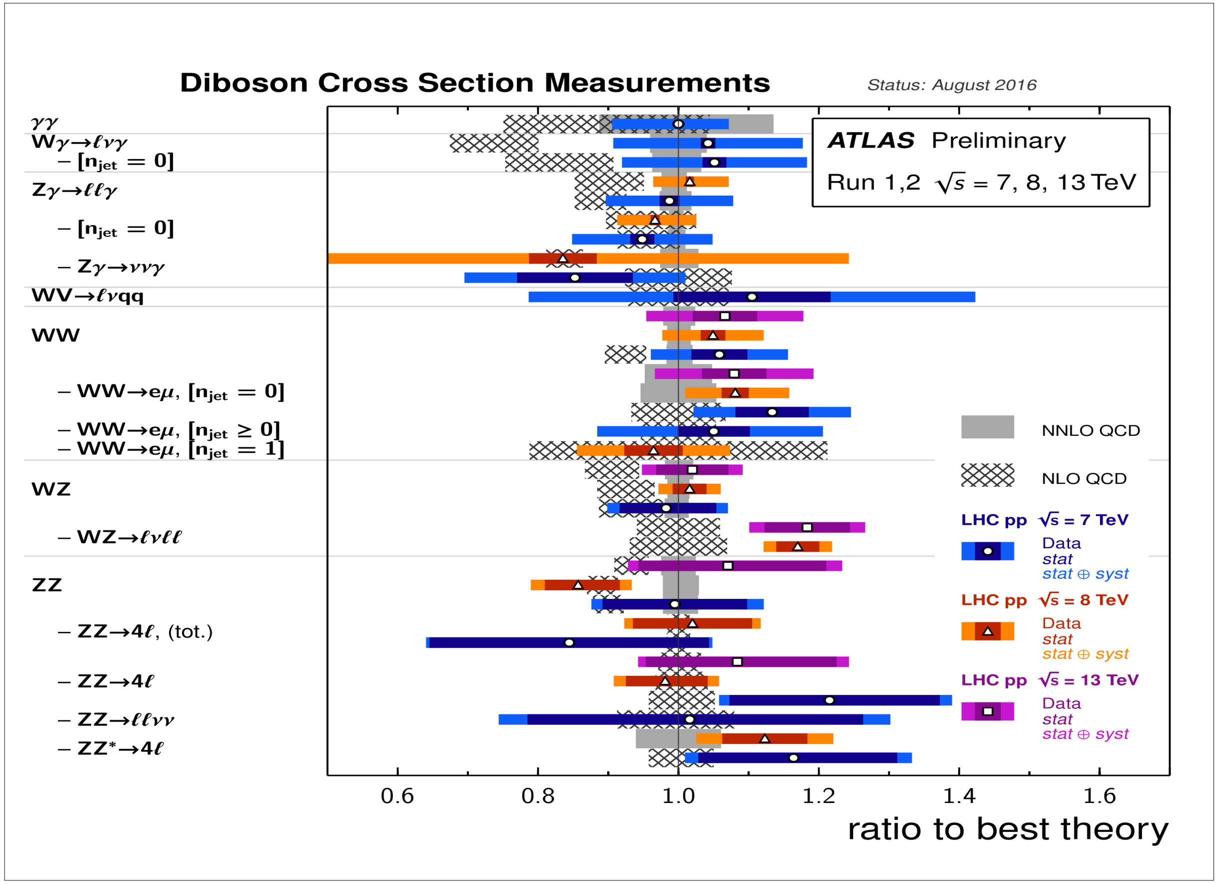
- Background to Higgs in H→VV decay channel
- Interference effects with Higgs in high mass tail → Higgs width constraints, probe unitarity
- Probe of trilinear EW gauge couplings
- Discovery potential for new physics
  (WW cross section discrepancy; 750 GeV diphoton excess)
- Test of pQCD in collider environment
- …

High experimental and theoretical precision required

Dibosons: Theory vs. Experiment

pp → VV known to NNLO*

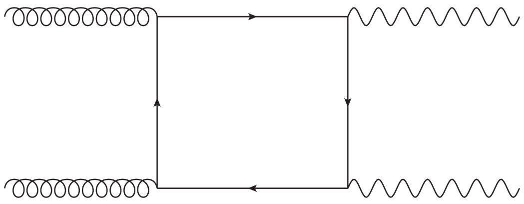
- Experimental errors ~ 10%-15% at Run II
- **Sensitivity to NNLO corrections**
- Target precision ~ 3%-5%



*(Catani, Cieri, de Florian, Ferrera, Grazzini '11; Grazzini, Kallweit, Rathlev, Torre '14; Cascioli *et al* '15; Gehrmann *et al* '15; Grazzini, Kallweit, Rathlev '15; Campbell, Ellis, Li, Williams '16)

Gluon fusion contribution

NNLO includes loop-induced (LO) **gluon fusion contribution gg** (for $\gamma\gamma$, $Z\gamma$, ZZ, WW)



Enhanced by large gluon flux – expected to be significant

- **ZZ:** (Cascioli *et al*, '14)
  - 60% of NNLO corrections
  - 1.44 pb / 16.91 pb at 13 TeV (~9%)
- **WW:** (Gehrmann *et al*, '14)
  - 35% of NNLO corrections
  - 4.4 pb / 118.7 pb at 13 TeV (~4%)

- $\gamma\gamma$: NLO corrections to *gg* known (Bern, Dixon, Schmidt, '02)
- $Z\gamma$: *gg* negligible (Grazzini, Kallweit, Rathlev, '15)

Gluon fusion at NLO

- Expect **large corrections** to $gg \to VV$

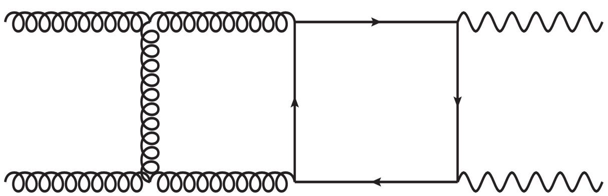
  (gluon-initiated production of light colorless final states – cf. Higgs production)
- Residual NNLO scale uncertainty ~ 2%-3%
  - Similar to NLO scale uncertainty 3%-4%
  - Dominated by **LO-like** *gg* scale uncertainty
- Corrections dependent on fiducial cuts (Binoth *et al*, '08)
- Leading corrections to interference effects with Higgs amplitudes

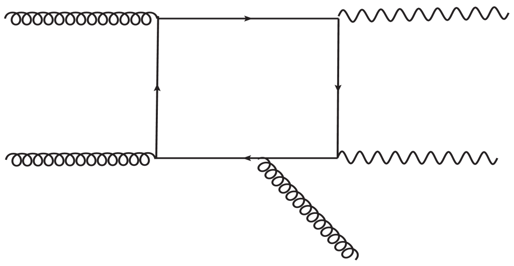
→ NLO corrections to $gg \to VV$

Outline of calculation

- **Two-loop** amplitudes for $gg \to VV$
- **One-loop** amplitudes for $gg \to VV+g$
  - stable in soft/collinear limit
  - analytic+numerical unitarity methods
- **Single** soft/collinear singularities

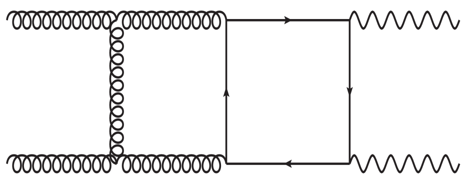
  (FKS, q_T subtraction)





Note: no *qg ->VVq* through a fermion loop

Two-loop amplitudes



- Available for massless internal lines

  (Caola, Henn, Melnikov, Smirnov, Smirnov '15;

  von Manteuffel, Tancredi '15)

- Extremely challenging for massive internal lines – cannot fully include third generation
- **ZZ:** include massless loops with 5 flavors* – effect ~1%
- **WW:** neglect third generation** – effect ~ 10%

*: neglecting vector-axial triangle diagrams, suppressed by top mass

**: except in SR real radiation amplitudes

Results: gg → ZZ

- Z bosons generated with BW about m_Z
- Include leptonic decays $ZZ \to e^+e^-\mu^+\mu^-$
- Use NNPDF3.0 and $\mu_0 = 2m_Z$ (scale variation: $\mu = \mu_0/2$ and $\mu = 2\mu_0$)

- At $\sqrt{s} = 8$ TeV

$$\sigma_{gg,\mathrm{LO}} = 0.97^{+0.3}_{-0.2}\ \mathrm{fb} \qquad \sigma_{gg,\mathrm{NLO}} = 1.8^{+0.2}_{-0.2}\ \mathrm{fb}$$

Increase by k-factor **1.85** (1.6 – 2.1 across scale range)

- At $\sqrt{s} = 13$ TeV

$$\sigma_{gg,\mathrm{LO}} = 2.8^{+0.7}_{-0.6}\ \mathrm{fb} \qquad \sigma_{gg,\mathrm{NLO}} = 4.7^{+0.4}_{-0.4}\ \mathrm{fb}$$

Increase by k-factor **1.67** (1.4 – 1.9 across scale range)

Impact on pp → ZZ at NNLO

- gg contribution to pp → ZZ at NNLO increased by 80% at 8 TeV and 70% at 13 TeV
- This increases the NNLO corrections from 12% → 18% at 8 TeV and 16% → 23% at 13 TeV

$$\sigma_{\mathrm{NLO}} = 7.369^{+2.8\%}_{-2.3\%}\ \mathrm{pb}$$

$$\sigma_{\mathrm{NNLO}} = 8.284^{+3.0\%}_{-2.3\%}\ \mathrm{pb}$$

$$\sigma_{\mathrm{NNLO+gg,NLO}} = 8.7\ \mathrm{pb}$$

(Cascioli *et. al*., '14)

undecayed ZZ

- Beyond expected ~3% scale variation in NNLO results.
- Other N^3LO corrections could have impact

Results: gg → WW

- W bosons generated on-shell
- Include leptonic decays $W^+W^- \to \nu_e e^+ \mu^- \bar{\nu}_\mu$
- Use NNPDF3.0 and $\mu_0 = m_W$ (scale variation: $\mu = \mu_0/2$ and $\mu = 2\mu_0$)
- At $\sqrt{s} = 8$ TeV

$$\sigma_{\mathrm{gg,LO}} = 20.9^{+6.8}_{-4.8}\ \mathrm{fb} \qquad \sigma_{\mathrm{gg,NLO}} = 32.2^{+2.3}_{-3.1}\ \mathrm{fb}$$

Increase by k-factor 1.54 (1.24 – 1.8 across scale range)

- At $\sqrt{s} = 13$ TeV

$$\sigma_{\mathrm{gg,LO}} = 56.5^{+15.4}_{-11.5}\ \mathrm{fb} \qquad \sigma_{\mathrm{gg,NLO}} = 79.5^{+4.2}_{-5.9}\ \mathrm{fb}$$

Increase by k-factor 1.4 (1.2 – 1.6 across scale range)

Impact on pp → WW at NNLO

- 13 TeV cross sections (Gehrmann *et. al.*, '14, undecayed WW)

$$\sigma_{\text{NLO}} = 106.0^{+4.1\%}_{-3.2\%}\ \text{pb} \quad \sigma_{\text{NNLO}} = 118.7^{+2.5\%}_{-2.2\%}\ \text{pb}$$

- Include *BR(W → lν)* = 0.108

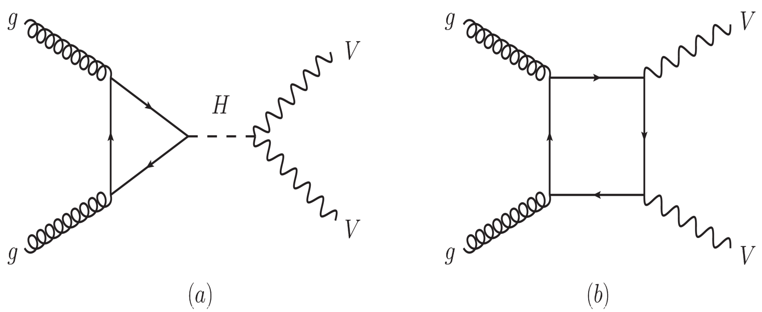
$$\sigma_{\text{NLO}} = 1.24\ \text{pb} \qquad \sigma_{\text{NNLO}} = 1.38\ \text{pb}$$

- 35% of NNLO corrections from gg $\Rightarrow \sigma_{gg} \simeq 51.8\ \text{fb}$
- Increased to 79.5 fb by NLO corrections
- Increases NNLO corrections by ~2%

$$\sigma_{\text{NNLO+gg,NLO}} \simeq 1.41\ \text{pb}$$

- Within scale uncertainty bands of NNLO results

Interference with Higgs



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

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

- ~10% of H → VV events above $2m_V$ (Kauer, Passarino '12)
- Independent of Higgs width ➡ **indirect constraint** on Higgs width* (Caola, Melnikov ‘13)
- **Strong destructive interference** at high energies ➡ probe **unitarizing behavior** of Higgs (connected to EWSB)

* Under certain assumptions – Englert, Spannowsky ‘13; Englert, Soreq, Spannowsky ‘14

Higgs width constraints

- CMS : $\Gamma_H < 13\ \mathrm{MeV}$
- Interference known at **LO only**
  - NLO corrections expected to be large
  - Scale uncertainty affects width constraint
- Approximated by **signal** k-factors – unclear if this is justified

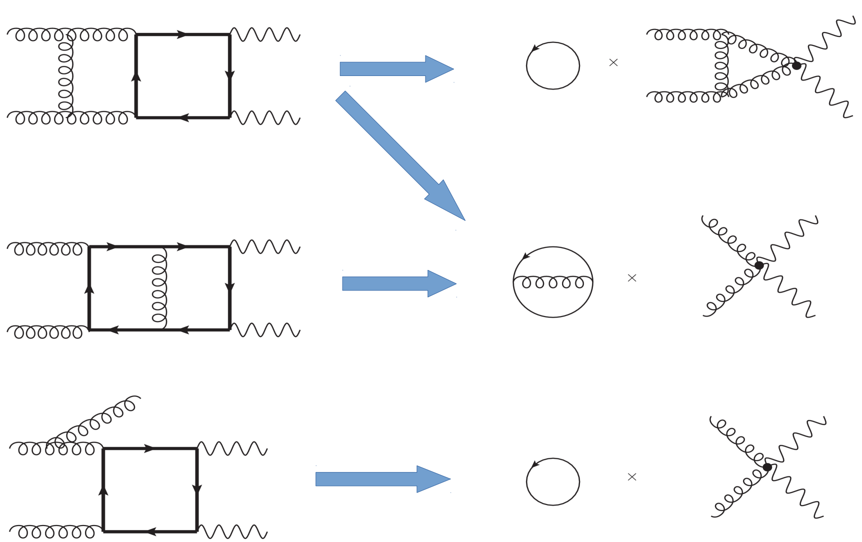
Obtain NLO QCD corrections separately for signal, background and interference terms

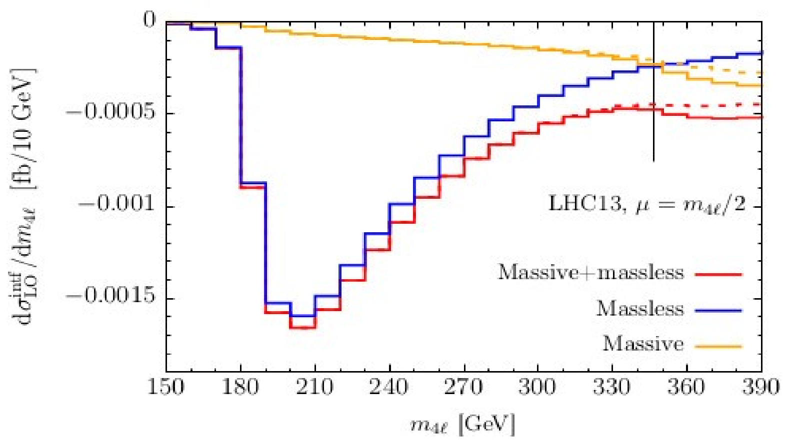
$gg \to (H) \to ZZ$: Top Mass Expansion

Need massive two-loop amplitudes!

→ 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)

gg → *(H)* →*ZZ* Results: Cross Sections

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

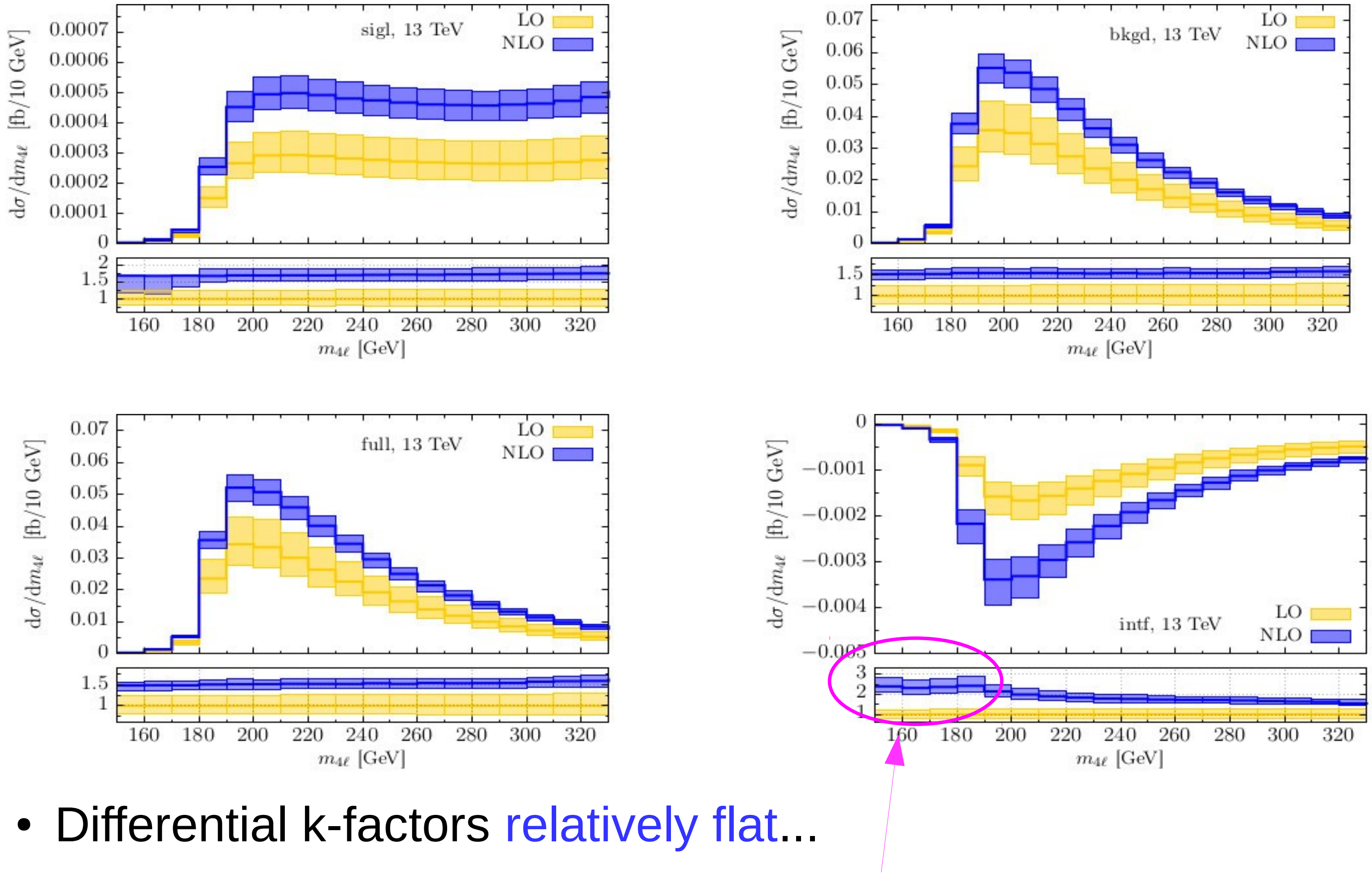
$$\sigma^{\rm bkgd}_{\rm LO} = 2.90^{+0.77}_{-0.58}\ {\rm fb}, \qquad \sigma^{\rm bkgd}_{\rm NLO} = 4.49^{+0.34}_{-0.38}\ {\rm fb}$$

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

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

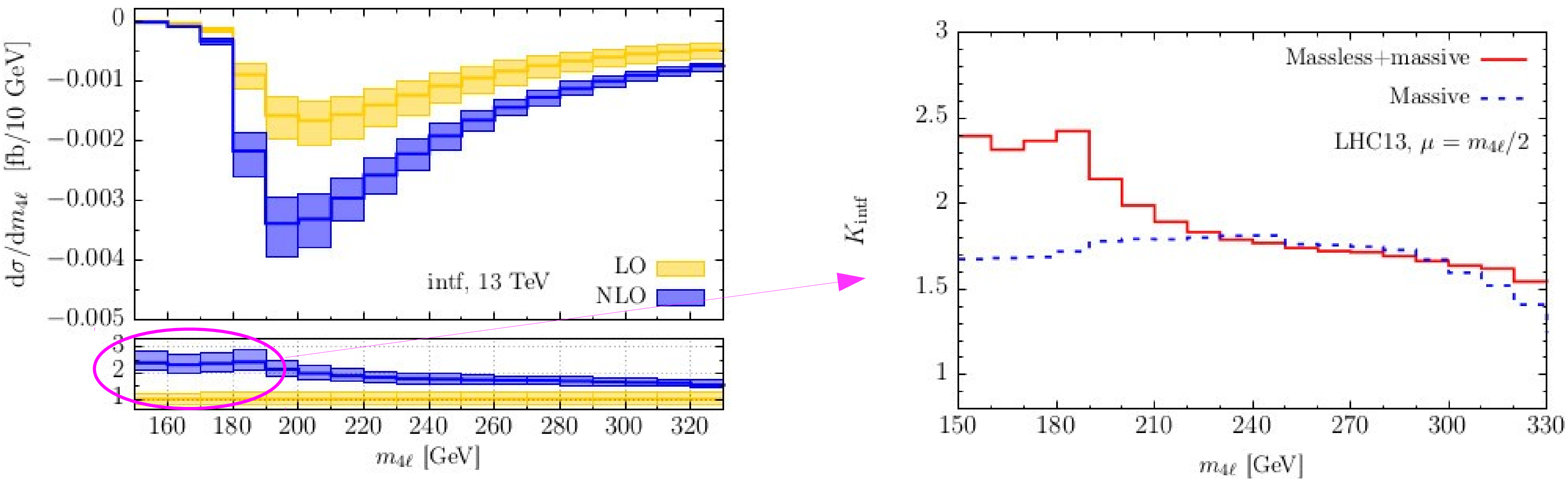
- Destructive interference ~ **5%**
  - ~ 4 x larger than signal, order of magnitude smaller than background
  - Can use specialized cuts needed to enhance relative to signal and background
- Scale uncertainty: 20%-30% at LO, 10% at NLO
- $K_{\rm sigl} = 1.72 \qquad K_{\rm bkgd} = 1.55 \qquad K_{\rm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

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



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

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

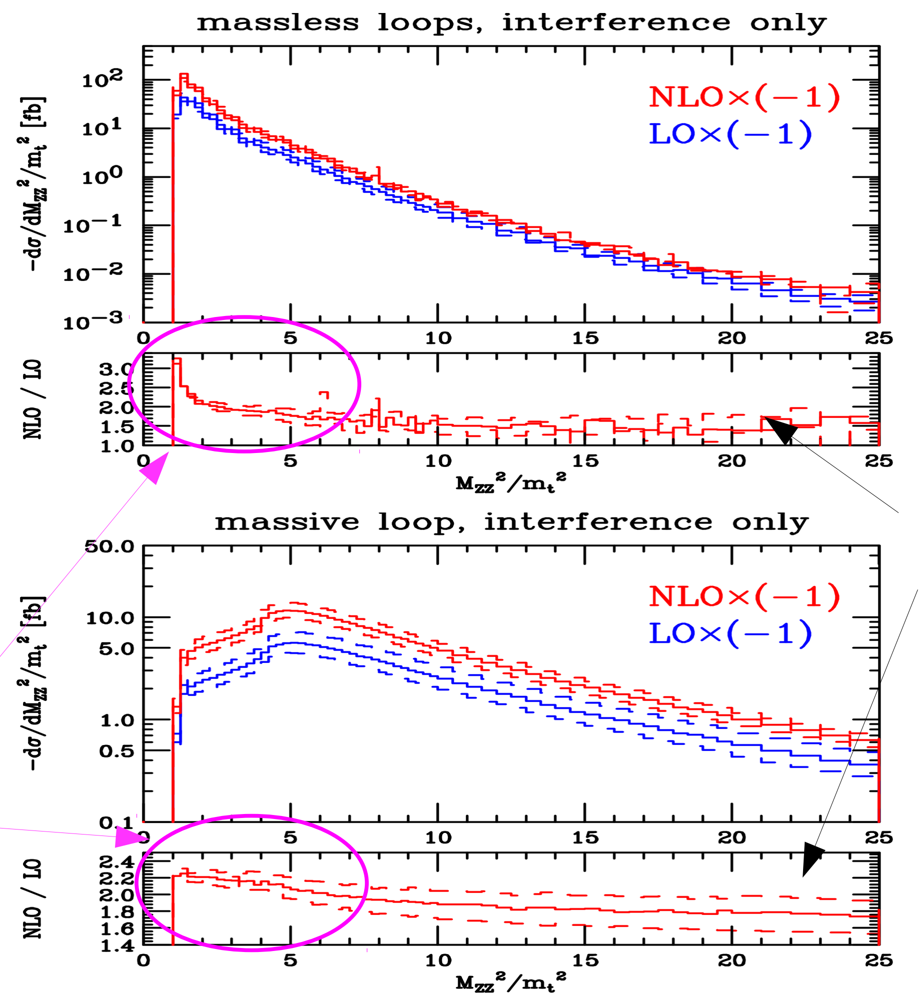


- Massless loop dominates near $2m_Z$ threshold, drives k-factor behavior

Comparison with similar work

Campbell, Czakon, Ellis, Kirchner, 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

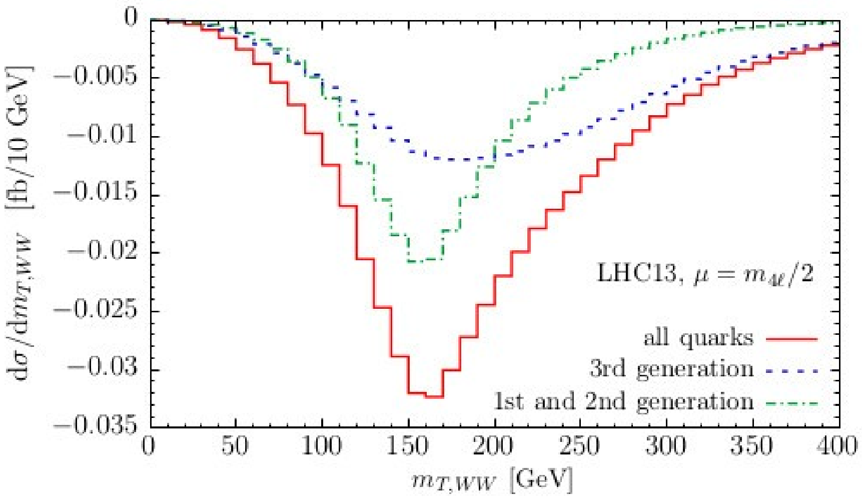


K-factor flat in high-energy tail

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*

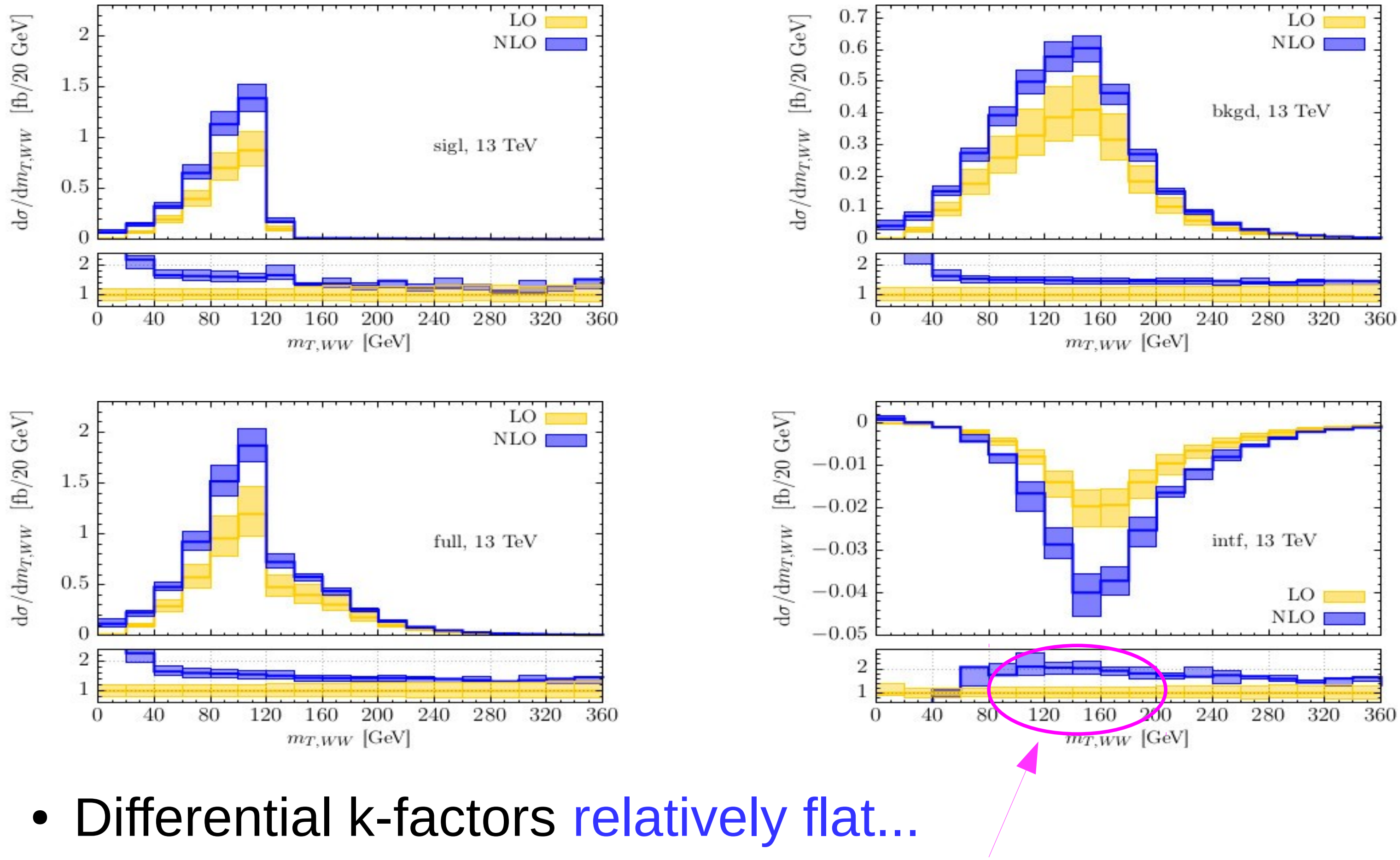
$gg \to (H) \to WW$ Results: Cross Sections

$$\sigma_{\rm LO}^{\rm signal} = 48.3^{+10.4}_{-8.4}\ {\rm fb}, \qquad \sigma_{\rm NLO}^{\rm signal} = 81.0^{+10.5}_{-8.2}\ {\rm fb}$$
$$\sigma_{\rm LO}^{\rm bkgd} = 49.0^{+12.8}_{-9.7}\ {\rm fb}, \qquad \sigma_{\rm NLO}^{\rm bkgd} = 74.7^{+5.5}_{-6.2}\ {\rm fb}$$
$$\sigma_{\rm LO}^{\rm intf} = -2.24^{+0.44}_{-0.59}\ {\rm fb}, \qquad \sigma_{\rm NLO}^{\rm intf} = -4.15^{+0.47}_{-0.54}\ {\rm fb}$$
$$\sigma_{\rm LO}^{\rm full} = 95.0^{+22.6}_{-17.6}\ {\rm fb}, \qquad \sigma_{\rm NLO}^{\rm full} = 151.6^{+15.4}_{-13.9}\ {\rm fb}.$$

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

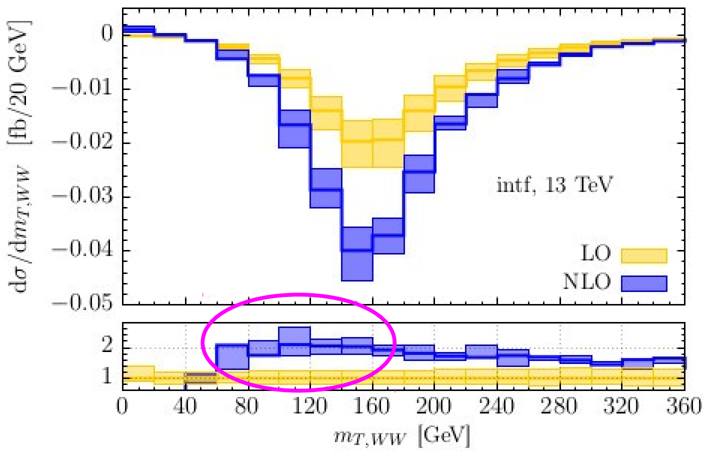
  → fairly close to geometric mean

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



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

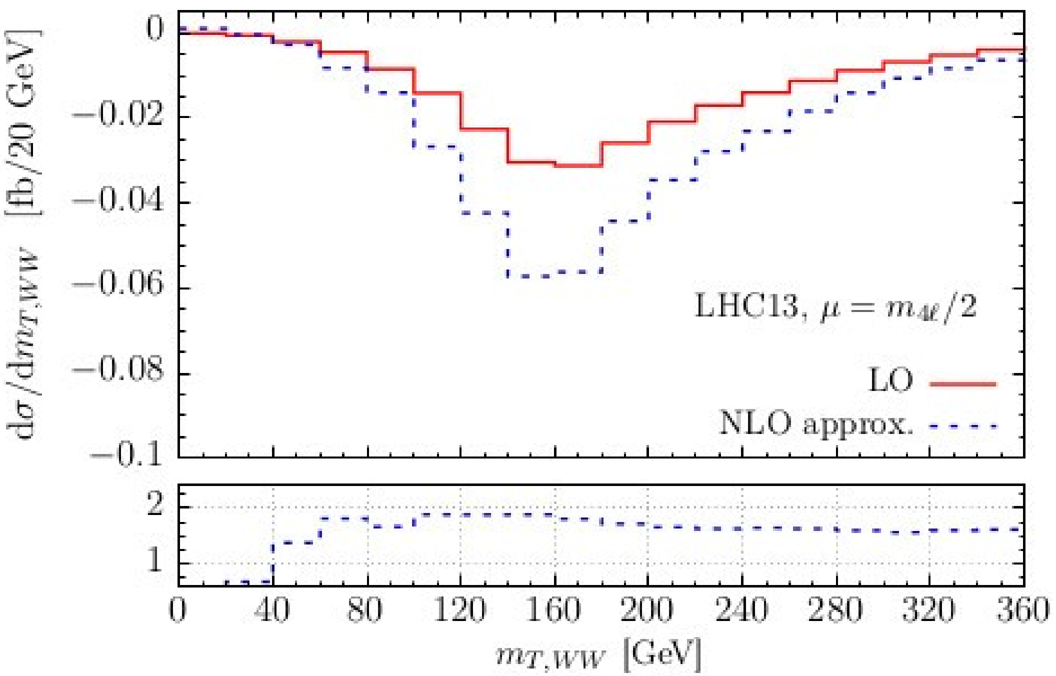
$gg \to (H) \to WW$ Results: Estimating effect of 3rd generation



- 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

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



Conclusions (I)

- NLO corrections to gg → ZZ, WW calculated (massless loops only)
- k factors ~1.6 at 8 TeV and ~1.4 at 13 TeV (for $\mu = m_V$)
- Increase NNLO pp → ZZ cross sections by ~4% (larger than NNLO scale uncertainty) and pp → WW cross sections by ~2% (comparable to NNLO scale uncertainty)

Conclusions (II)

- Computed NLO corrections to $gg \to ZZ$ and $gg \to WW$, 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 $2m_Z$ 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!