NLO Corrections to VV production through gluon fusion

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Rencontres de Moriond, QCD & High Energy Interactions

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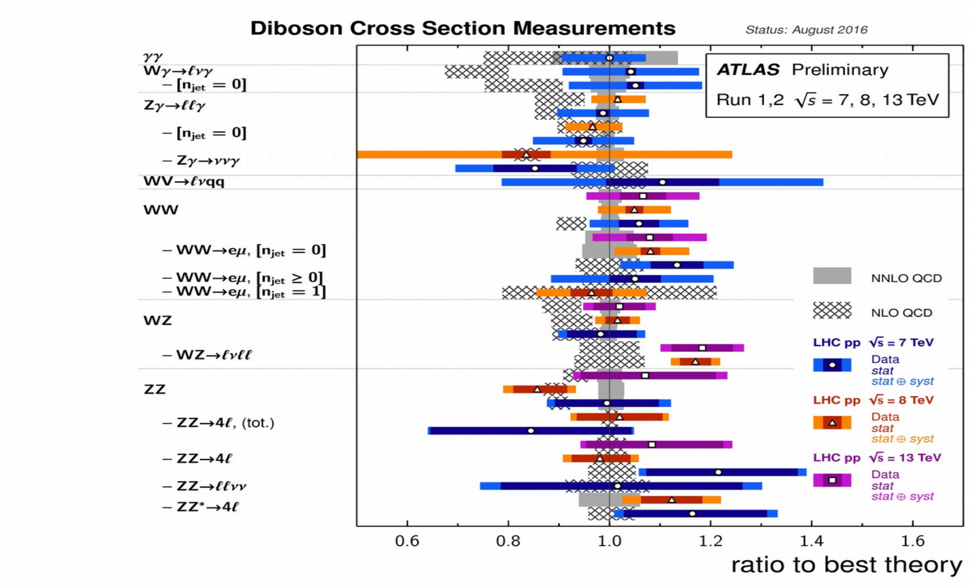
Fabrizio Caola, Kirill Melnikov, R.R., Lorenzo Tancredi [hep-ph/1509.06734, hep-ph/1511.0861]
Fabrizio Caola, Matthew Dowling, Kirill Melnikov, R.R., Lorenzo Tancredi [hep-ph/1605.04610]

Diboson production

- Important process at LHC:
  - Background to Higgs in $H \to VV$ decay channel
  - Interference effects with Higgs in high mass tail
  - 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
- All $pp \to VV$ known at NNLO*
- Experimental errors ~ 10%-15% at Run II
- **Sensitivity to NNLO corrections**
- Target precision ~ 3%-5%

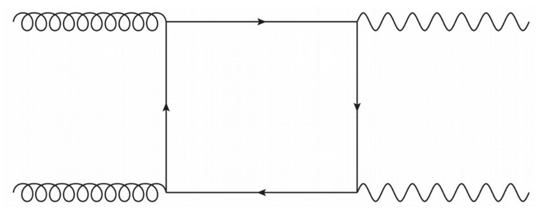


See talks by Stefan Kallweit, Marius Wiesemann

*(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; Grazzini, Kallweit, Rathlev, Wiesemann ‘16, ’17)

Gluon fusion contribution

NNLO includes loop-induced (LO) **gluon fusion contribution** (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)

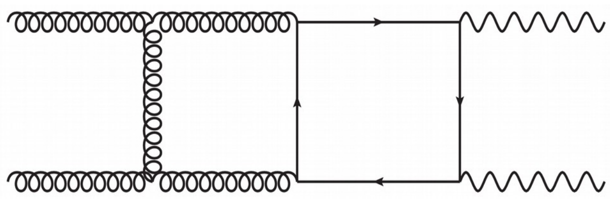
- **LO-like** scale uncertainty
  - NNLO scale uncertainty ~ 2%-3% – similar to NLO scale uncertainty ~ 3%-4%

- Leading contributions to interference effects with Higgs amplitudes

→ NLO corrections to $gg \to VV$

Outline of calculation

Two-loop amplitudes for *gg→VV*



- Available for massless internal lines

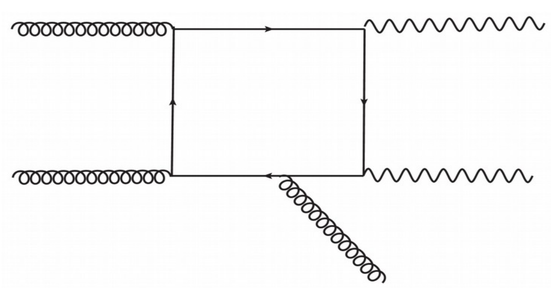
  (Caola, Henn, Melnikov, Smirnov, Smirnov '15;

  Von Manteuffel, Tancredi '15)

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

One-loop amplitudes for *gg→VV+g*

- stable in soft/collinear limit
- analytic+numerical unitarity methods



Results: $gg \to ZZ$

- 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

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

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

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

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

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

Impact on *pp* → *ZZ* at NNLO

- N^3LO correction to *pp* → *ZZ*
- This increases the NNLO corrections from 12% → 18% at 8 TeV and 16% → 23% at 13 TeV

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

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

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

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

undecayed ZZ

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

Results: $gg \to WW$

- 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)

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

- Include *BR(W → lν)* = 0.108

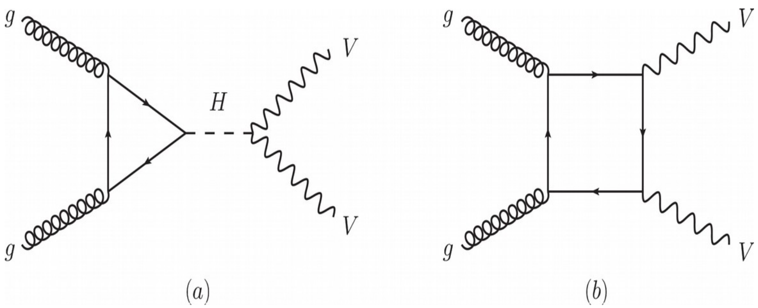
$$\sigma_{\mathrm{NLO}} = 1.24\ \mathrm{pb} \qquad \sigma_{\mathrm{NNLO}} = 1.38\ \mathrm{pb}$$

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

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

- Within scale uncertainty bands of NNLO results

Interference with Higgs



$$|A_{ZZ}|^2 = |A_H|^2 + |A_b|^2 + 2\mathrm{Re}[A_H A_b^*]$$
$$\rightarrow \sigma_{\mathrm{full}} = \sigma_{\mathrm{sigl}} + \sigma_{\mathrm{bkgd}} + \sigma_{\mathrm{intf}}$$

- Important for off-shell Higgs production
- ~ 10% of *H* → *VV* events 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]

Indirect constraints on Higgs width

Situation prior to Moriond:

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

Impact of higher order corrections:

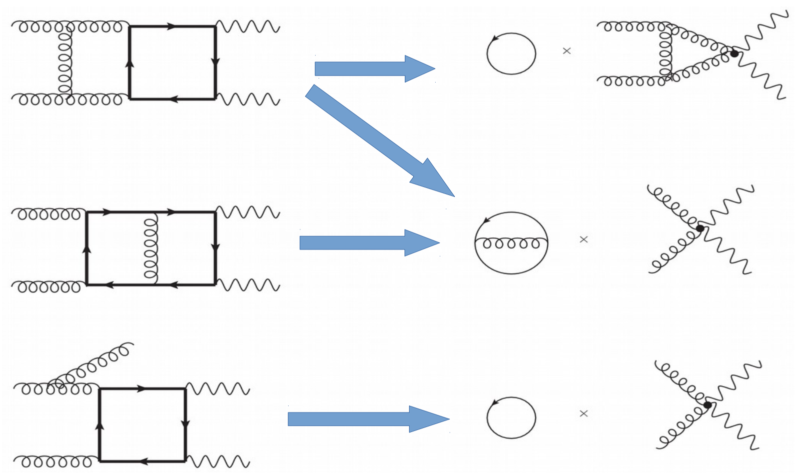
- Known to be **large** for signal (k ~ 1.7)
- Expected to be *similar for* background and interference
- Above results approximate background and interference corrections with those of signal
- Background and interference now known to **NLO**:

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

  Caola, Dowling, Melnikov, R.R., Tancredi [hep-ph/1605.04610]

Top Mass Expansion

- Massless *gg* → *VV* amplitudes as before
- Higgs amplitudes well-known
- Need massive two-loop *gg* → *VV*
  ➡ expand in s/m_t^2
- Keep terms to $(s/m_t^2)^4$
- Expect to be valid for partonic energies $s \lesssim 4m_t^2$
- Checked at LO: good approximation for $m_{4\ell} \leq 2m_t$



[Dowling, Melnikov ‘15]

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

- Full leptonic decay: $gg \to ZZ \to e^+e^-\mu^+\mu^-$ at 13 TeV LHC
- Dynamical scale $\mu_F = \mu_R = \{m_{4\ell}/4, m_{4\ell}/2, m_{4\ell}\}$
- Minimal cuts:
  - $150 \text{ GeV} \leq m_{4\ell} \leq 340 \text{ GeV}$
  - $p_{T,j} < 150 \text{ GeV}$
  - $60 \text{ GeV} \leq m_{\ell\ell} \leq 120 \text{ GeV}$
- Further cut possible

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

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

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

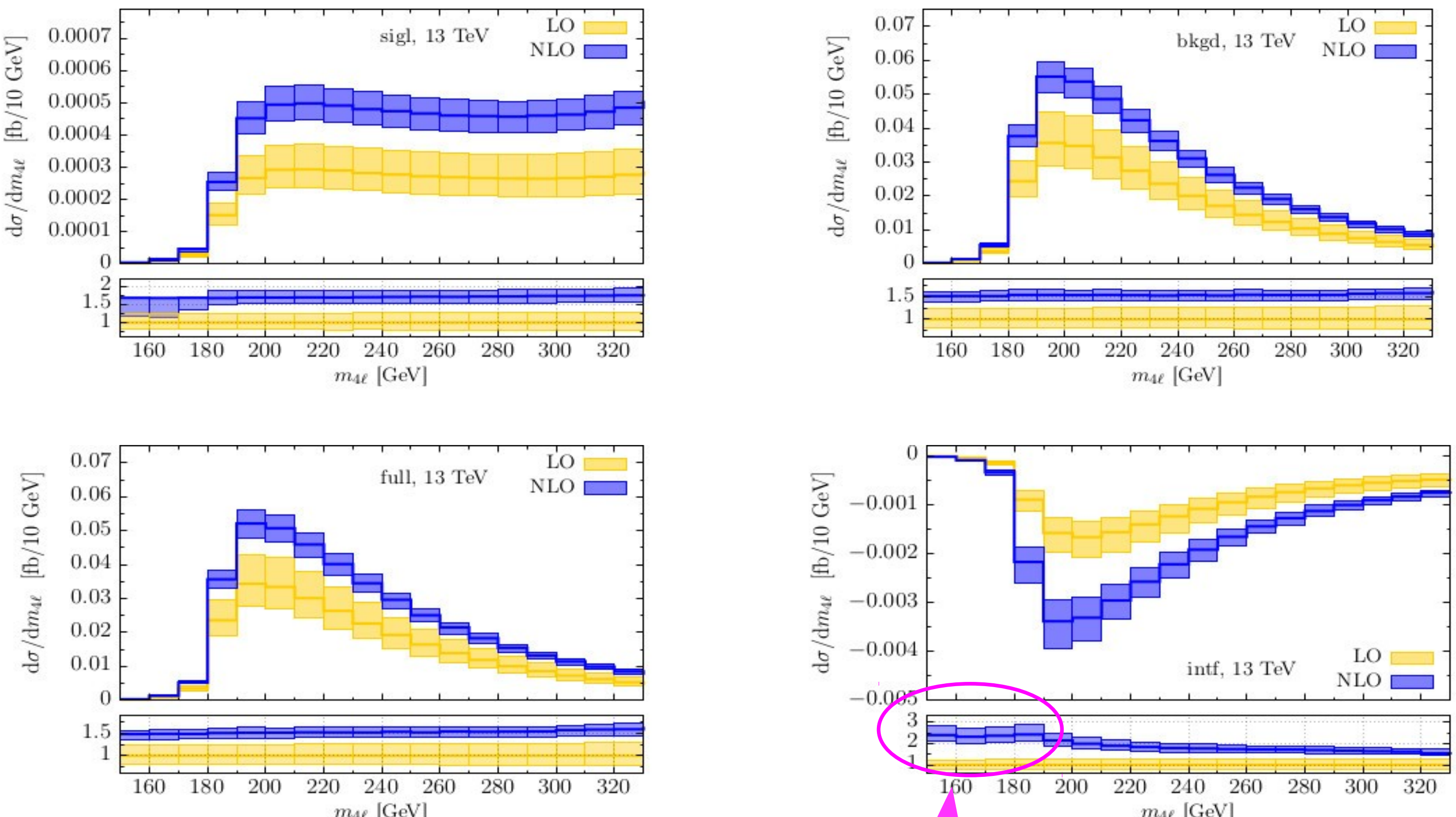
$$\sigma_{\rm LO}^{\rm intf} = -0.154^{+0.031}_{-0.04}\ {\rm fb}, \qquad \sigma_{\rm NLO}^{\rm intf} = -0.287^{+0.031}_{-0.037}\ {\rm fb}$$

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

- 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
- $K_{\rm sigl} = 1.72 \qquad K_{\rm bkgd} = 1.55 \qquad K_{\rm intf} = 1.86$

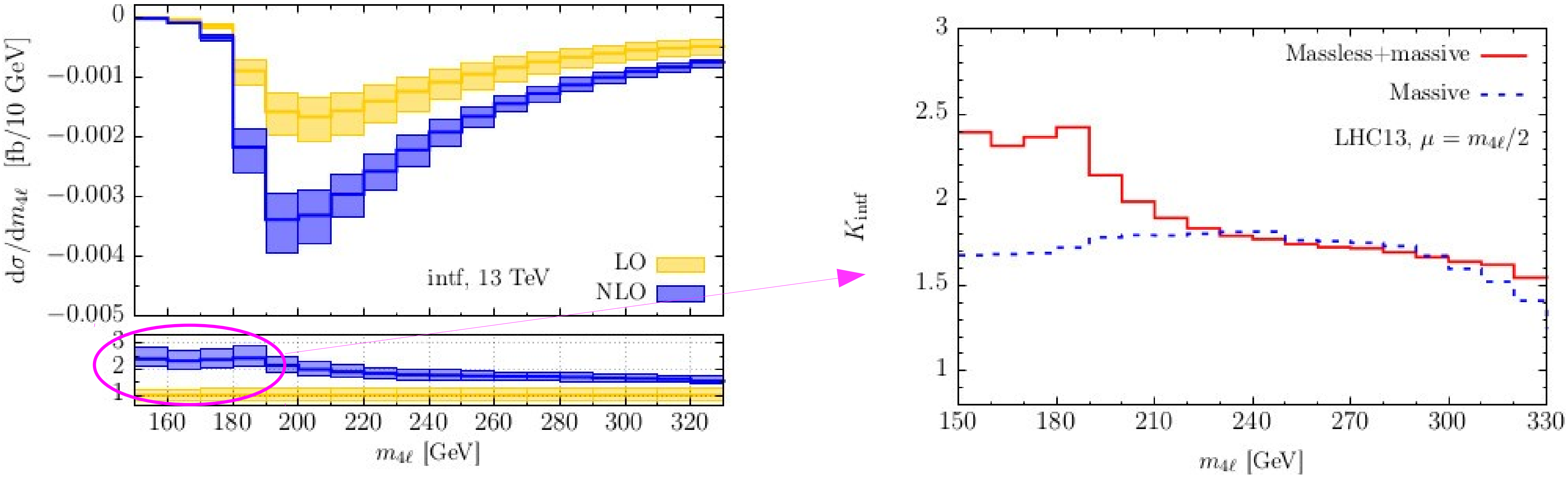
  → fairly close to geometric mean

gg → (H) →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



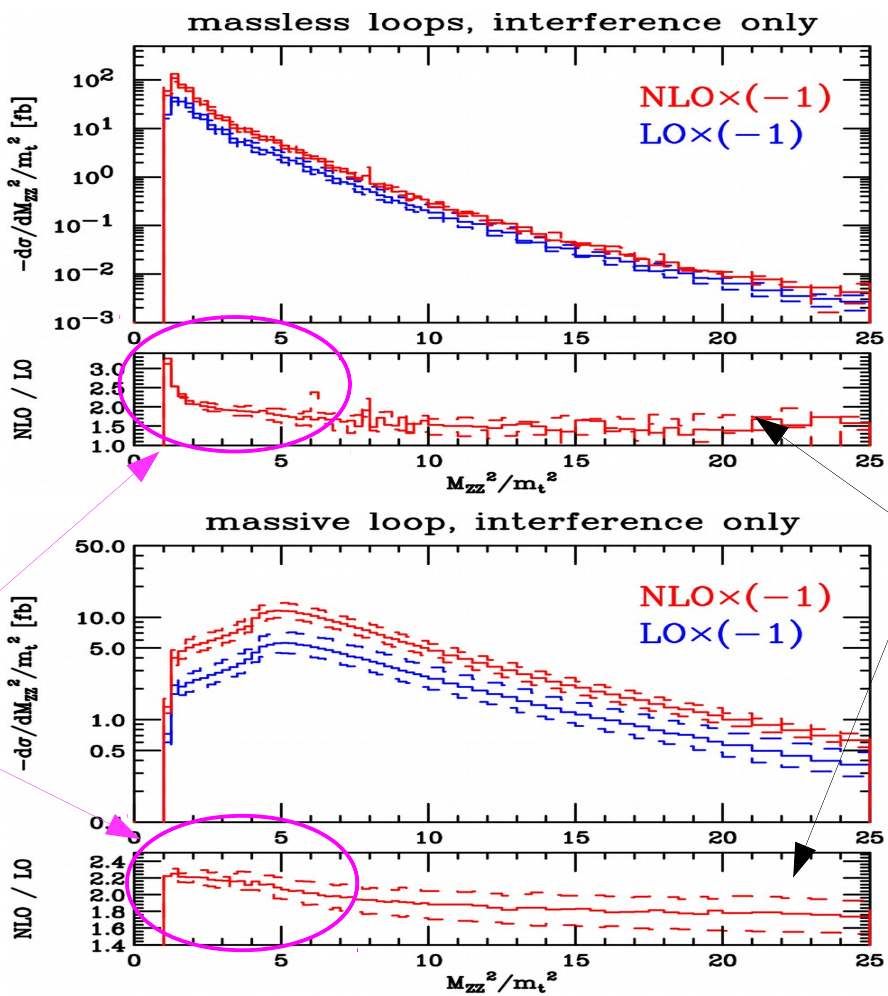
- Massless loop dominates near $2m_Z$ threshold, drives k-factor behavior

Comparison with similar work

Campbell, Czakon, Ellis, Kirchner [hep-ph:1605.01380]

- Results extended beyond $2m_t$ threshold using conformal mapping and Padé approximations

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



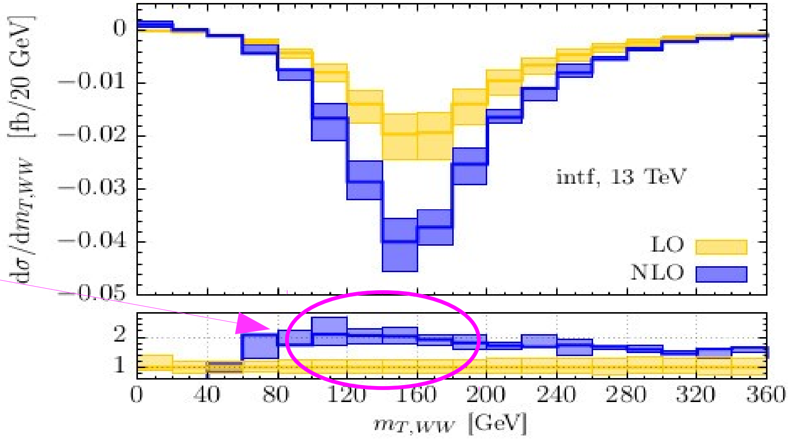
K-factor flat in high-energy tail

$gg \to (H) \to WW$

Similar analysis for *WW*

- Neglect third generation (non-negligible impact on interference)
- **Partial results only**

- Destructive interference ~ 2%
- Similar k-factors to *ZZ*
- Similarly k-factor behavior around $2m_w$ peak



Conclusions

- NLO corrections to gg → ZZ, WW calculated (massless loops only)
- k-factor ~ 1.4-1.7
- Increase NNLO *pp* → *ZZ* cross sections by ~4% and *pp* → *WW* cross sections by ~2%
- NLO corrections to Higgs interference in *gg* → *ZZ* and *gg* → *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*
- Large k-factors ~ 1.85
- Significantly larger **near $2m_Z$ threshold** – driven by massless amplitudes – and drops off rapidly

ONGOING WORK

- Interface interference calculation with parton shower
  - *gg* → *ZZ* (massless) background in POWHEG BOX [Alioli, Caola, Luisoni, R.R. '16]
- Include quark-gluon channels (particularly important for PS)

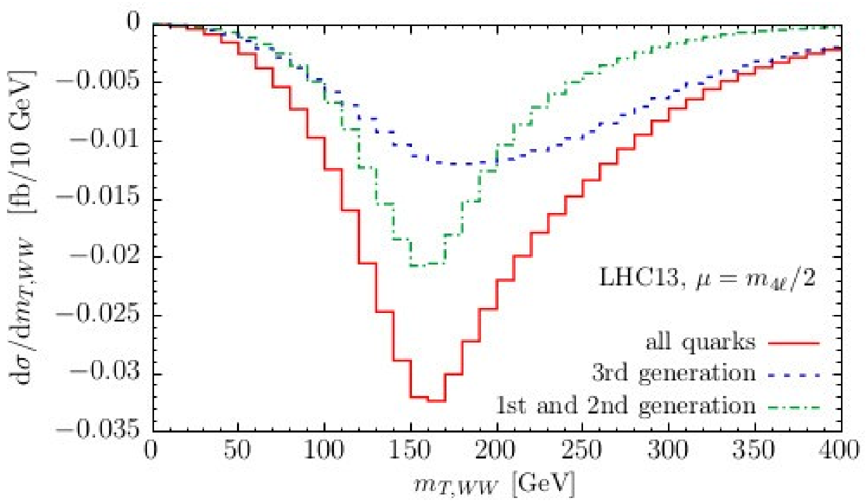
THANK YOU!

QUESTIONS?

BACKUP SLIDES

$gg \to (H) \to WW$

- 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 → *(H)* → *WW* Results: Cross Sections

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

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

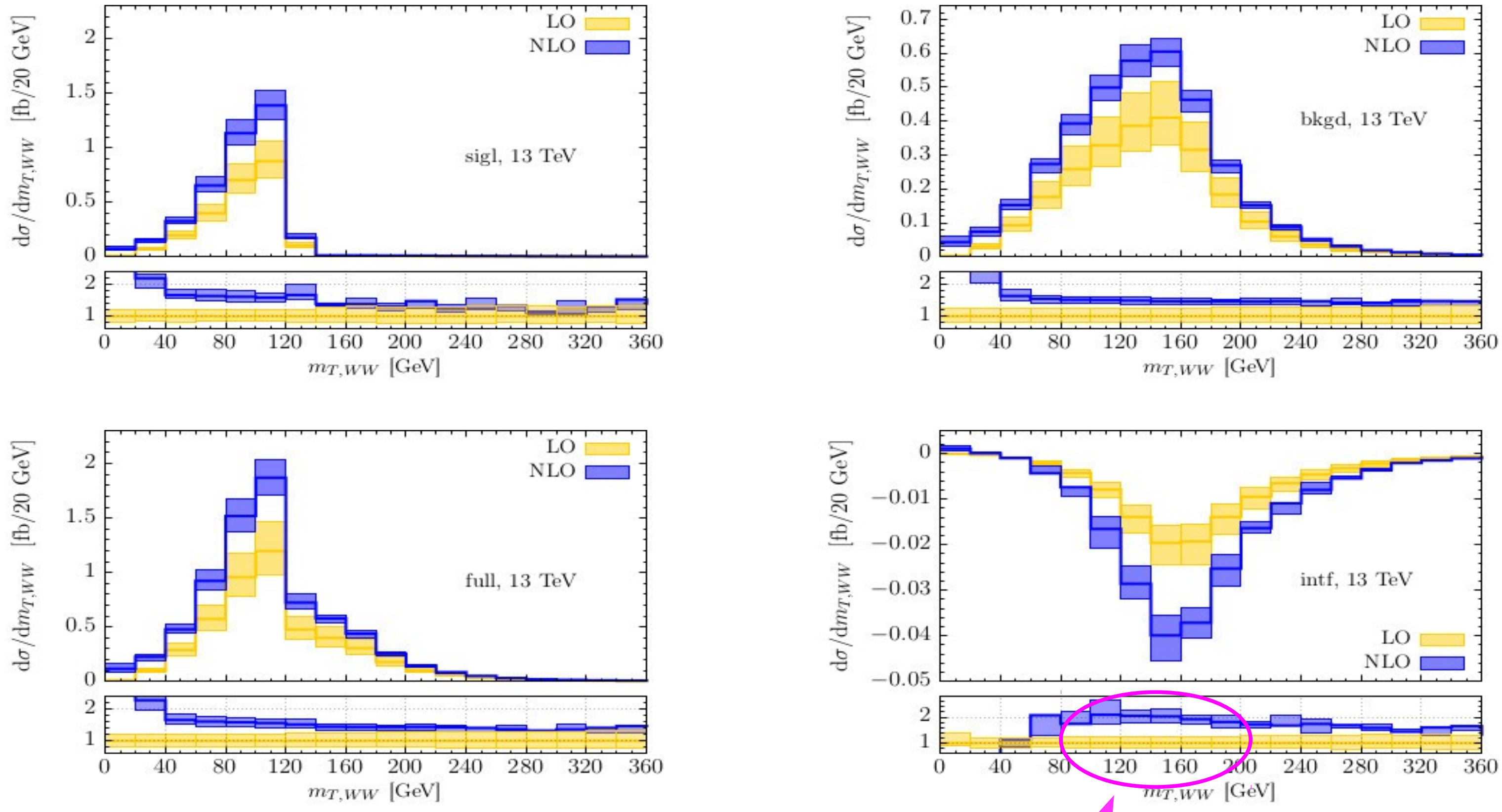
$$\sigma_{\rm LO}^{\rm intf} = -2.24^{+0.44}_{-0.59}\ {\rm fb}, \qquad \sigma_{\rm NLO}^{\rm intf} = -4.15^{+0.47}_{-0.54}\ {\rm fb}$$

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

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

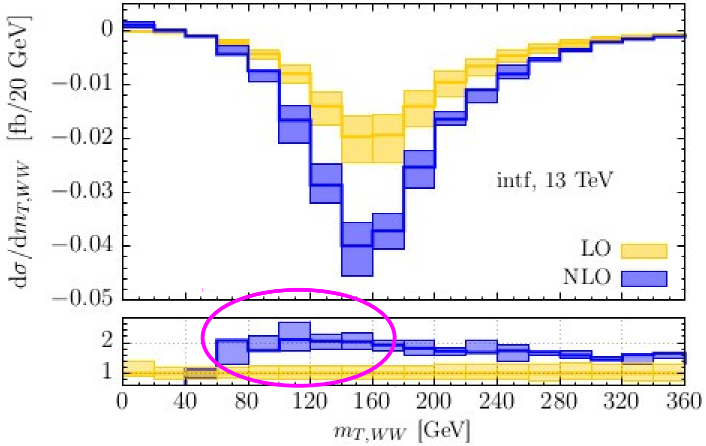
  → similar to *ZZ*

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



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

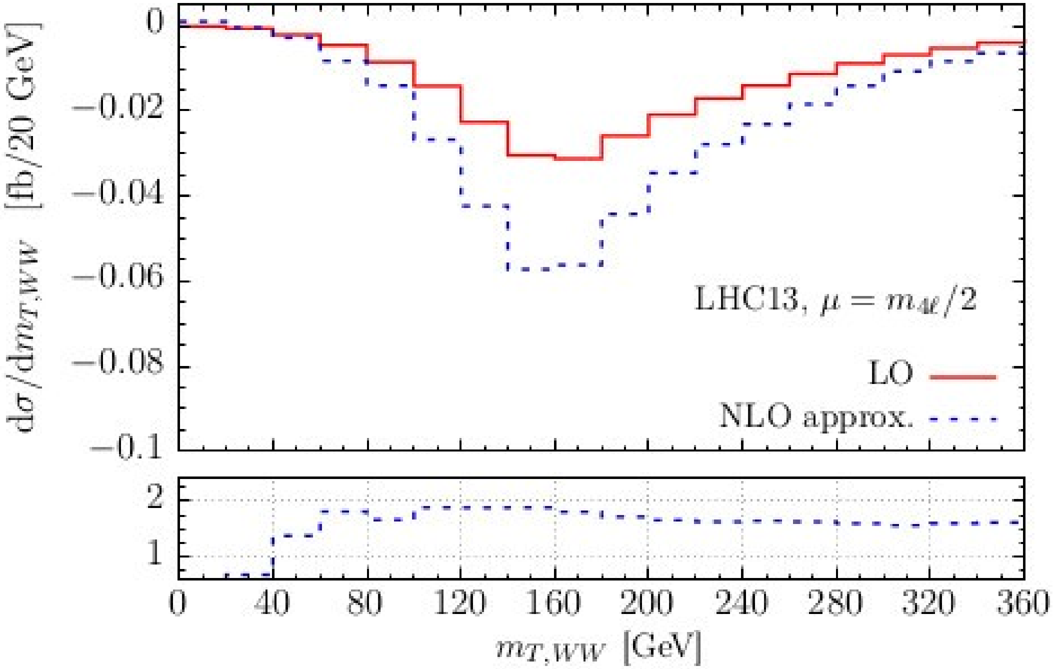
$gg \rightarrow (H) \rightarrow WW$ Results: Estimating effect of 3rd generation



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

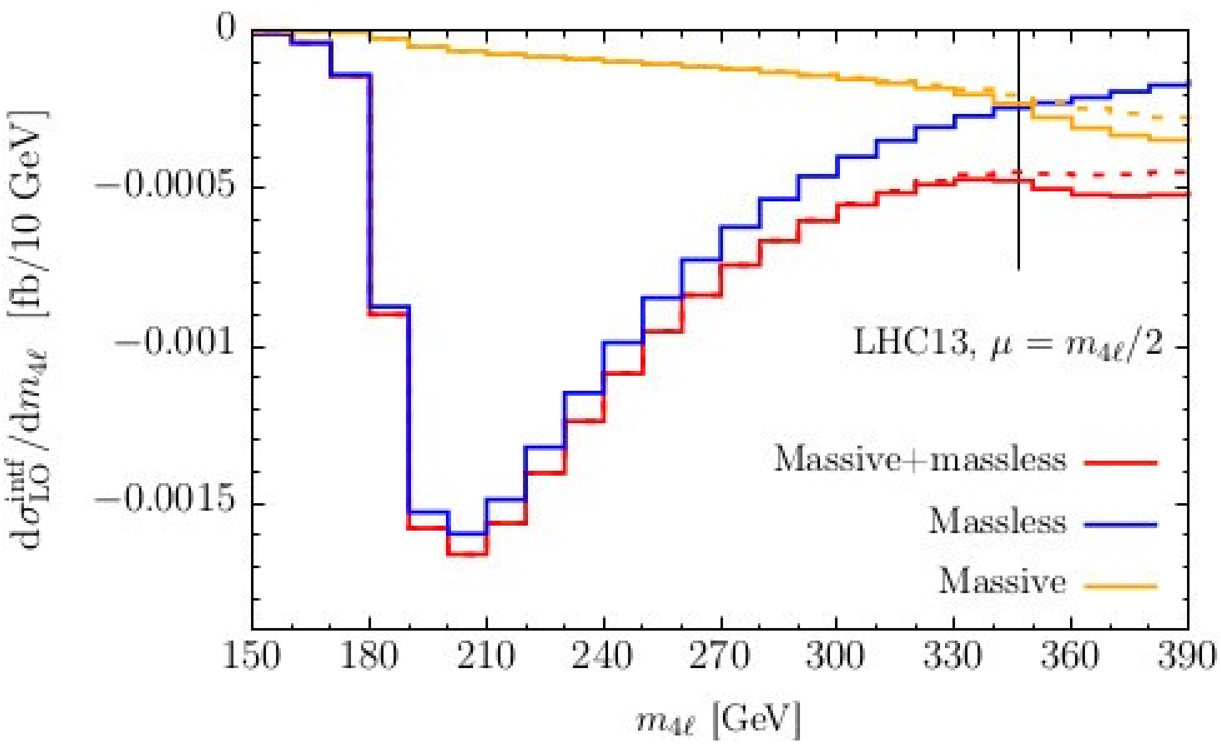
→ estimate by using LO results scaled by approximate k-factor

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

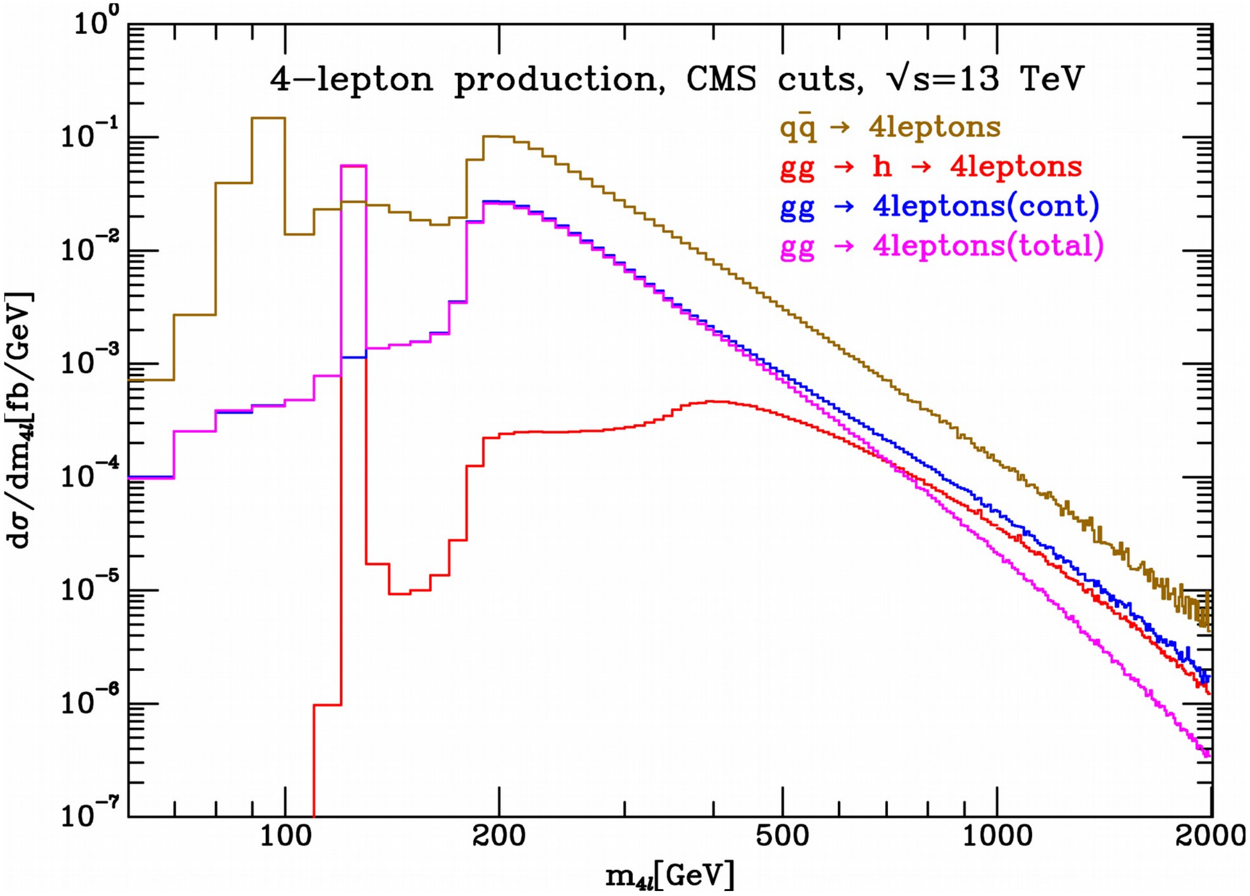


Validity of top mass expansion

- LO m_{4l} spectrum
- Exact result: solid; mass expansion: dashed
- Excellent agreement up to $2m_t$ and diverges afterwards



Signal, background, interference spectrum



Campbell, Ellis, Williams ‘13