Theory status of offshell Higgs production

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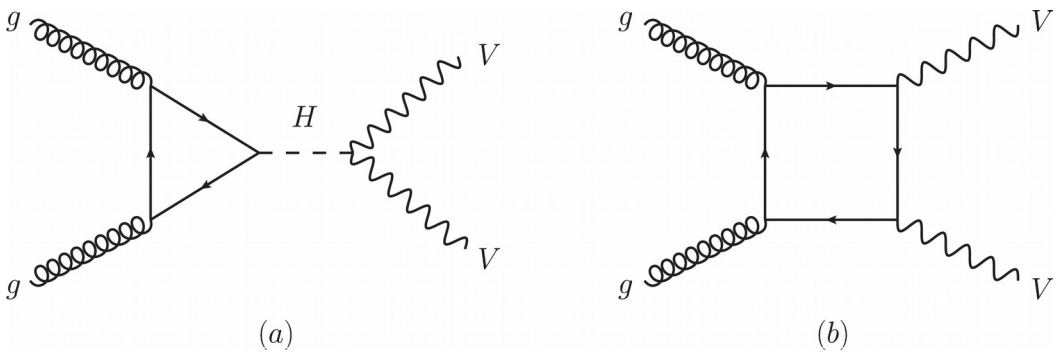
with F. Caola, M. Dowling, K. Melnikov, L. Tancredi, hep-ph/1605.04610

LHC Higgs Cross Section Working Group, Offshell subgroup meeting

CERN, 22 February 2018

Offshell Higgs production at LO

Consistent treatment in **offshell region** requires both signal $gg \to H \to ZZ$ and background $gg \to ZZ$ amplitudes



LO: amplitudes known with full mass dependence.

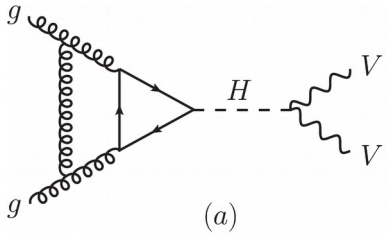
"signal" A_H "background" A_b

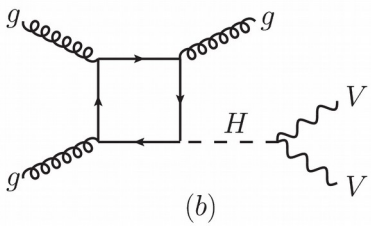
$$|A_{ZZ}|^2 = |A_H|^2 + |A_b|^2 + 2\mathrm{Re}[A_H A_b^*]$$

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

Offshell Higgs production at NLO

Known

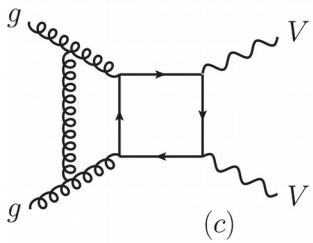


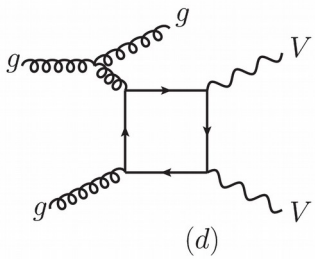


Known

Massless: known

Massive:
extremely difficult*

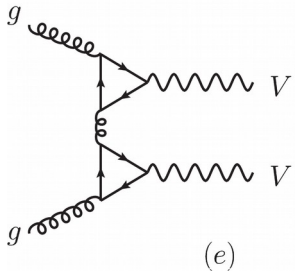


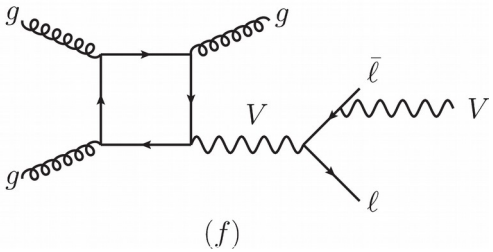


Massless: easy

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;

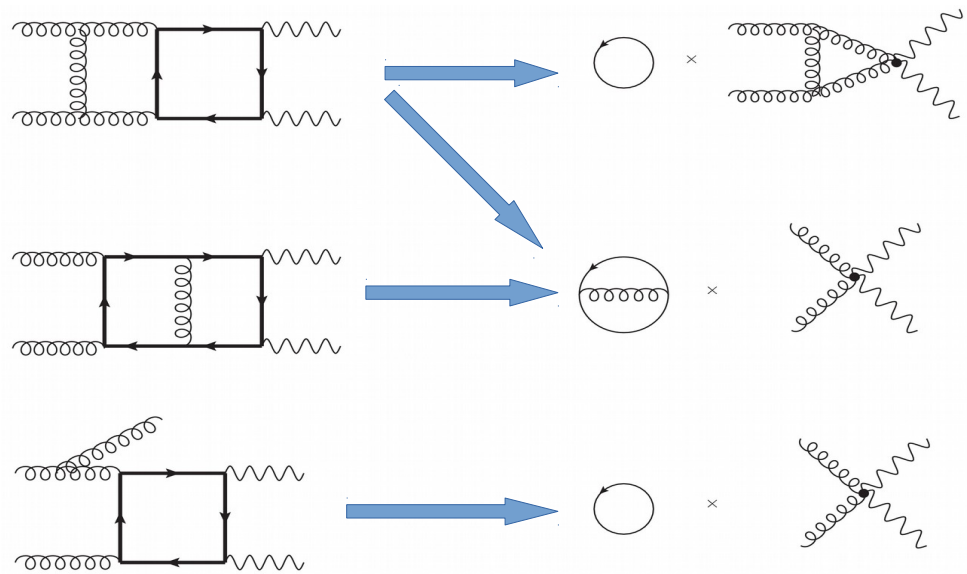
* but possibly within reach now

NLO calculations

Campbell, Czakon, Ellis, Kirchner, hep-ph/1605.01380	**Caola, Dowling, Melnikov, RR, Tancredi hep-ph/1605.04610**
Only interference.	Signal, background, and interference.
Onshell *Z* bosons, so $m_{ZZ} > 2m_Z$.	Offshell *Z* bosons.
Massive two-loop amplitudes computed in mass expansion to $(s/m_t^2)^6$	Massive two-loop amplitudes computed in mass expansion to $(s/m_t^2)^4$
Massive real emission amplitudes computed exactly – no need for jet veto.	Massive real emission amplitudes computed in mass expansion – **need to veto energetic jets.**
Results extended beyond $2m_t$ threshold using Padé approximant.	

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

Expand in s/m_t^2

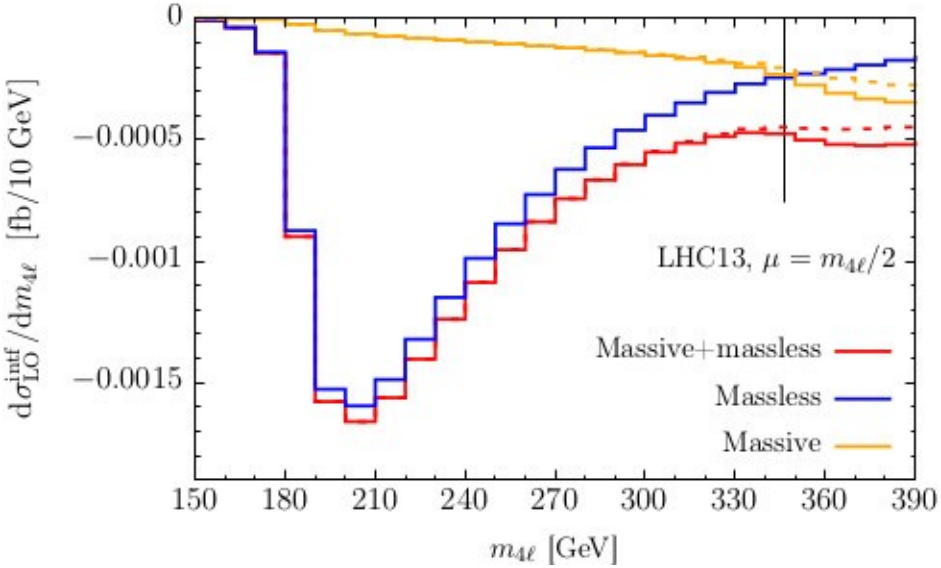


- Keep terms to $\left(s/m_t^2\right)^4$
- Expect to be valid for partonic energies $s \lesssim 4m_t^2$

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

- Cannot give reliable description of interference effects in high-mass region.
- Large window $150\ \mathrm{GeV} \lesssim m_{4\ell} \leq 2m_t$ where Higgs is offshell and we can study **interference effects at NLO.**

Necessity of jet veto

- Real radiation corrections computed in large mass expansion.
- These can give rise to energetic jet:
  - can lead to $\sqrt{s} > 2m_t$ even though $m_{4\ell} < 2m_t$
  - Expansion not valid.
- Comparing to interference effects for *H+j* with exact top mass: Campbell, Ellis, Furlan, RR '14

  ➡ jet requirement $p_{T,j} < 150\ \mathrm{GeV}$
- **Not** required in calculation of Campbell *et al.*

Quark-gluon channels

- **Quark-gluon fusion** $qg \to ZZq$ appears in NLO corrections.
- **Separately gauge invariant** so *in principle* they could be included.
- *In practice,* they cannot be distinguished from quark-gluon contributions to pp → ZZ at NNNLO.
- Not included in our calculation – suppressed by ratio gluon/quark luminosities.
- Contribution to interference ~ 4 smaller than *gg* channel [Campbell, Ellis, Furlan, RR '14]
- Warrants further study – any possible sensitivity to this channel should be approached with caution.

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:
  - $150\ \mathrm{GeV} \leq m_{4\ell} \leq 340\ \mathrm{GeV}$
  - $p_{T,j} < 150\ \mathrm{GeV}$
  - $60\ \mathrm{GeV} \leq m_{\ell\ell} \leq 120\ \mathrm{GeV}$

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

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

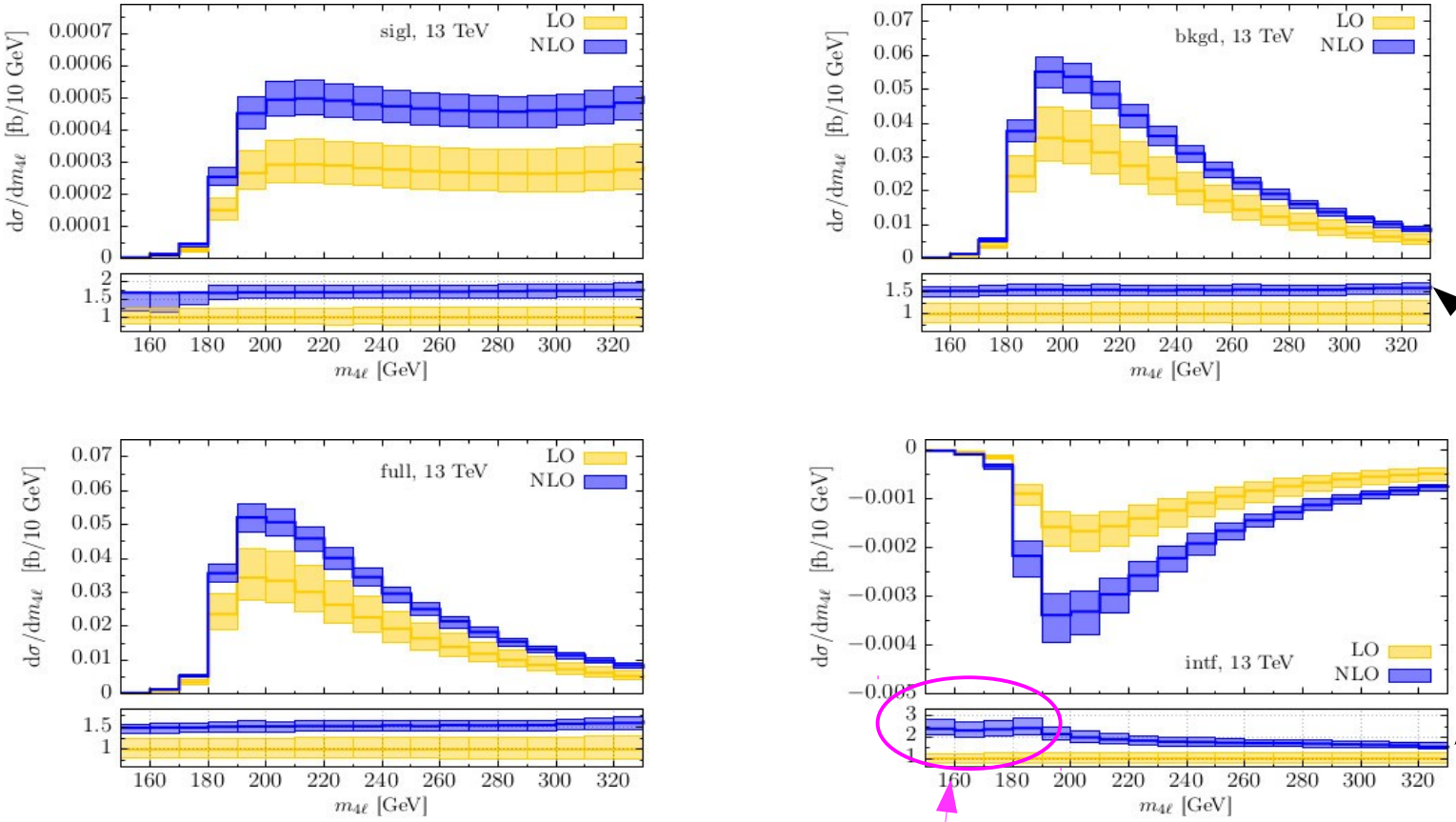
$$\sigma_{\rm LO}^{\rm bkgd} = 2.90^{+0.77}_{-0.58}\ {\rm fb}, \qquad \sigma_{\rm NLO}^{\rm bkgd} = 4.49^{+0.34}_{-0.38}\ {\rm fb}$$

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

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

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

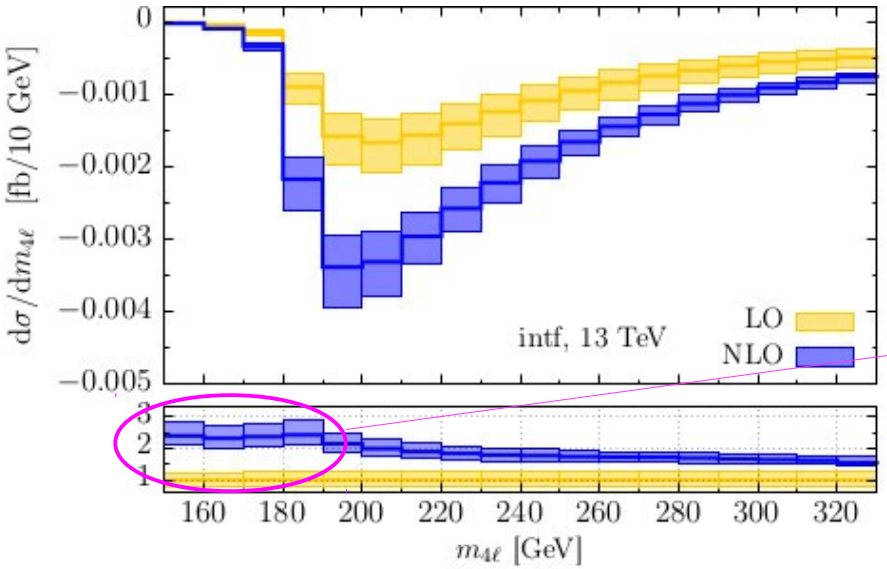
$gg \to (H) \to ZZ$ Results: Mass distributions

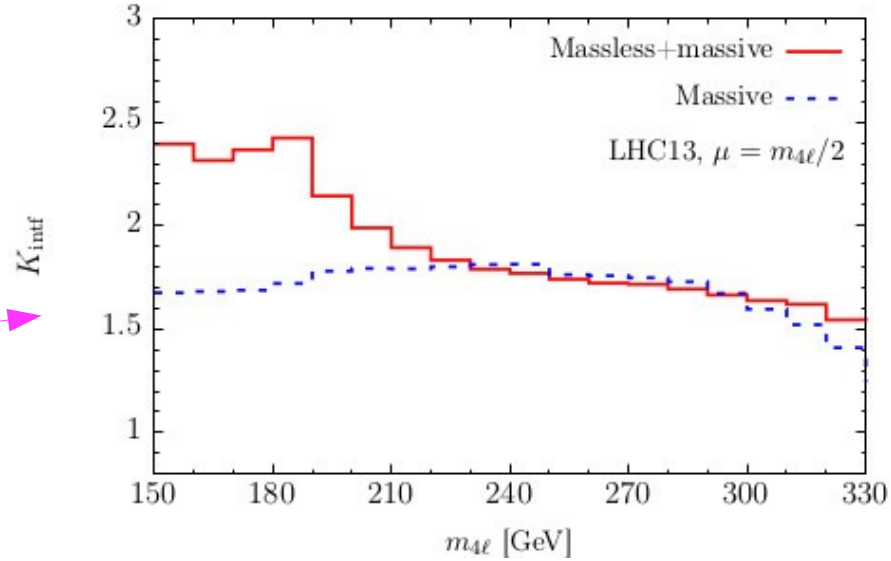


K-factors ~ 1.5 near $2m_t$ threshold

- 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

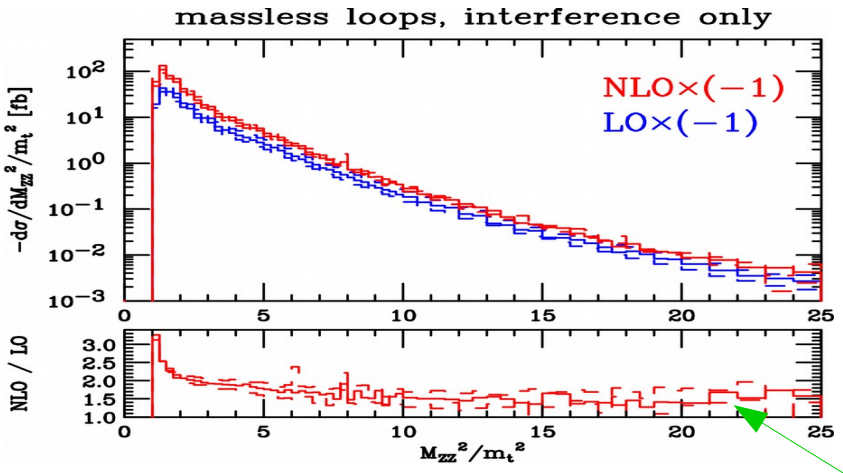
Going above the top threshold (I)

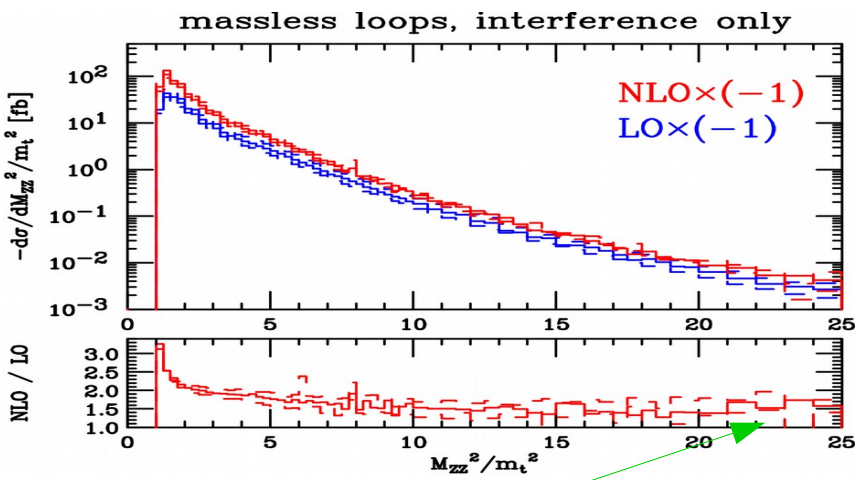
- Can consider interference with massless loops only:
  - Remove restrictions on $m_{4\ell}$ and jet veto.
  - But massive loops **dominate** interference above $2m_t$ threshold.
  - Unclear how to estimate uncertainty from neglecting massive loops.
- Numerical calculation of two-loop amplitudes **with full mass dependence** appears feasible:
  - $gg \to HH$ computed at NLO with full mass dependence. [Borowka *et al*, '16]
  - $H+j$ computed at NLO with full top mass dependence. [Jones, Kerner, Luisoni '18]

Going above the top threshold (II)

- Use Padé approximants to extend mass expansion above threshold

Campbell, Czakon, Ellis, Kirchner, '16





K-factor flat in high-energy tail

- Comparison of Padé approximants with exact results for *gg* → *HH* [Gröber, Maier, Rauh '17]:
  - Padé approximants based on mass expansion do not reproduce exact results very well.
  - Include threshold expansion ➡ dramatic improvement in agreement with exact results.

Beyond NLO...

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?

Conclusions

- Difficulty of computing massive two-loop amplitudes ➡ **top mass expansion.**
- Cannot use massive interference results in **high energy regimes** (high invariant mass or energetic jets).
- Below top threshold:
  - Interference k-factors ~ 1.86, slightly larger than signal or background.
  - Interference k-factor ~ 2.5 around m_{ZZ} peak; decreases to ~ 1.5 at top threshold.
- Above top threshold: massless interference only, Padé approximants? *Full top mass dependence within reach???*