$gg \rightarrow ZH$: NLO Differential Prediction

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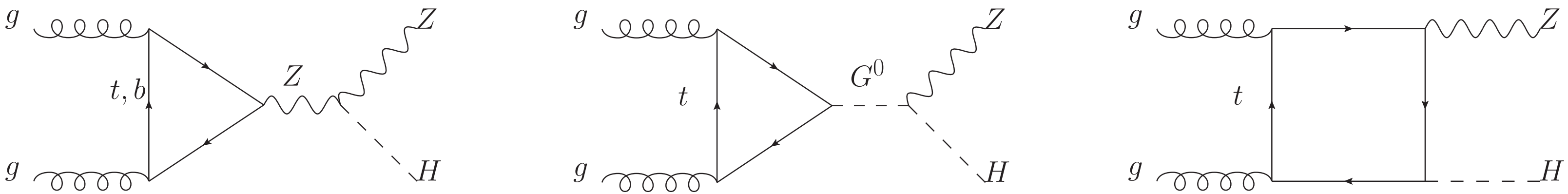
The 21th Workshop of the LHC Higgs Working Group, CERN - 6.12.24

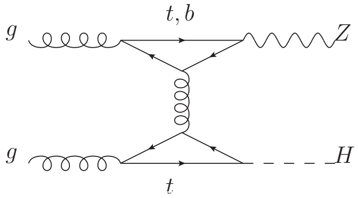
$gg \to ZH$ @ LO

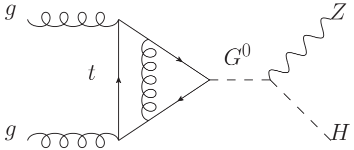


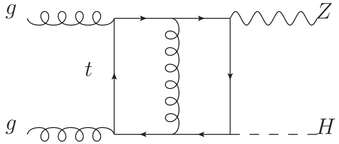
- O(α_s^2) correction to $\sigma(pp \to ZH)$
- NNLO suppression wrt to $q\bar{q} \to ZH$ compensated by larger gluon luminosity
- Contributes to ~ 6% of $\sigma(pp \to ZH)$ for $\sqrt{s} = 14$ TeV
- NLO QCD corrections required to stabilize theoretical prediction
  - ~25% scale uncertainty @ LO
  - NLO typically large for gg-initiated processes

$gg \to ZH$ @ NLO in QCD - Ingredients

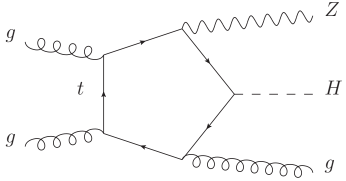
Virtual corrections (2 → 2, two loops) - interference with LO

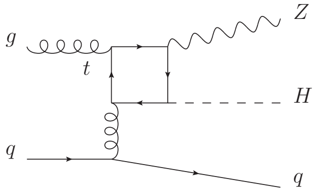


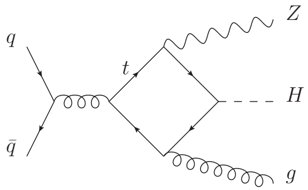




Real emission (2 → 3, one loop) - squared amplitudes

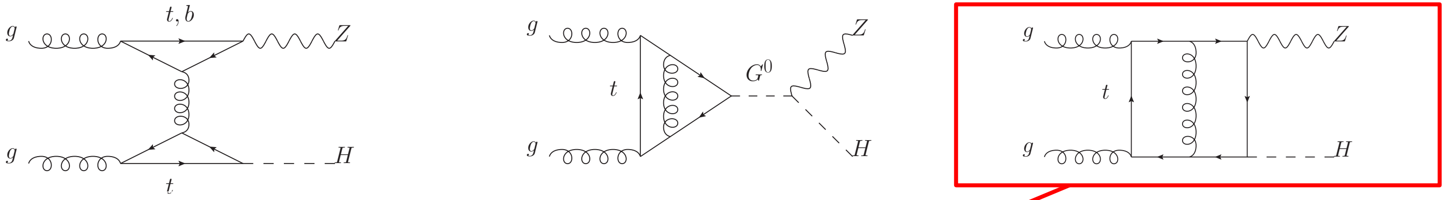






$gg \to ZH$ @ NLO in QCD - Ingredients

Virtual corrections ($2 \to 2$, two loops) - interference with LO



Main problem in the NLO calculation

Multi-scale (m_Z, m_H, m_t, s, t) two-loop box integrals

No full analytic results

Complete NLO Predictions

- Sector decomposition ⊕ High-Energy expansion
  [Chen, Davies, Heinrich, Jones, Kerner, Mishima, Schlenk, Steinhauser - 2204.05225]

Virtual corrections
- pySecDec for $p_T < 200\,\mathrm{GeV}$
- HE exp for $p_T > 200\,\mathrm{GeV}$

Real emission
- GoSam & in-house C++ code

- pT expansion ⊕ High-Energy expansion [Degrassi, Gröber, MV, Zhao - 2205.02769]

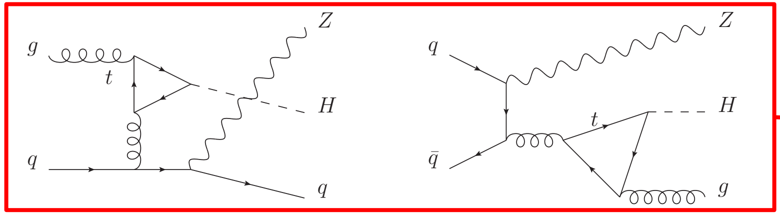
Virtual corrections
- pT exp for $|\hat{t}| < 4m_t^2$
- HE exp for $|\hat{t}| > 4m_t^2$

Real emission
- RECOLA2 [Denner, Lang, Uccirati - 1711.07388]
- MadGraph5 [Alwall et al. - 1405.0301]

- O(100%) NLO corrections observed
- Scale uncertainties reduced: ~25% → ~15%

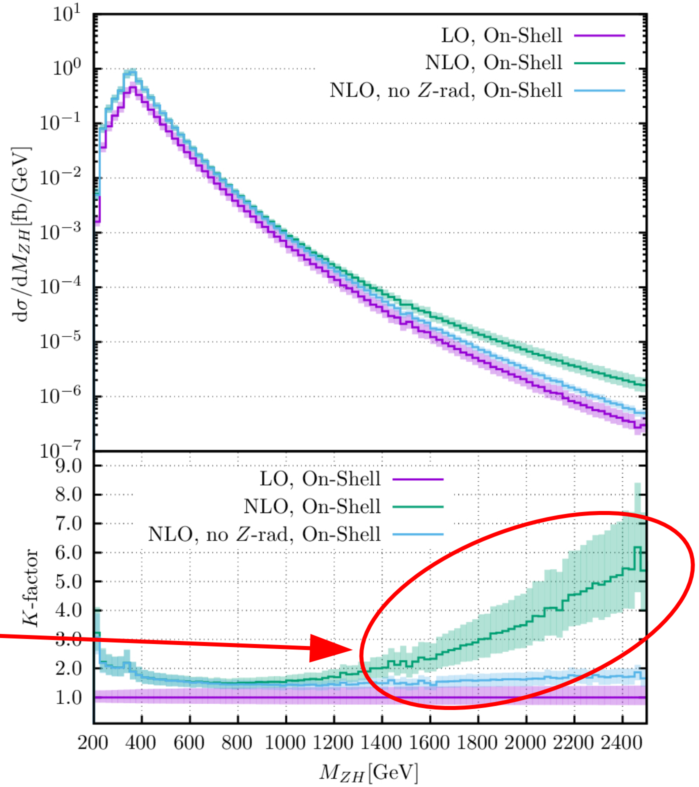
High-Energy Tails – Z Radiation

- K-factor rapidly increasing for $M_{ZH} > 1\,\mathrm{TeV}$
- Effect due to real-emission diagrams where the Z is radiated from an open fermion line
- Not included in [Wang, Xu, Xu, Yang - 2107.08206] [Chen et al. - 2204.05225]



Dominant

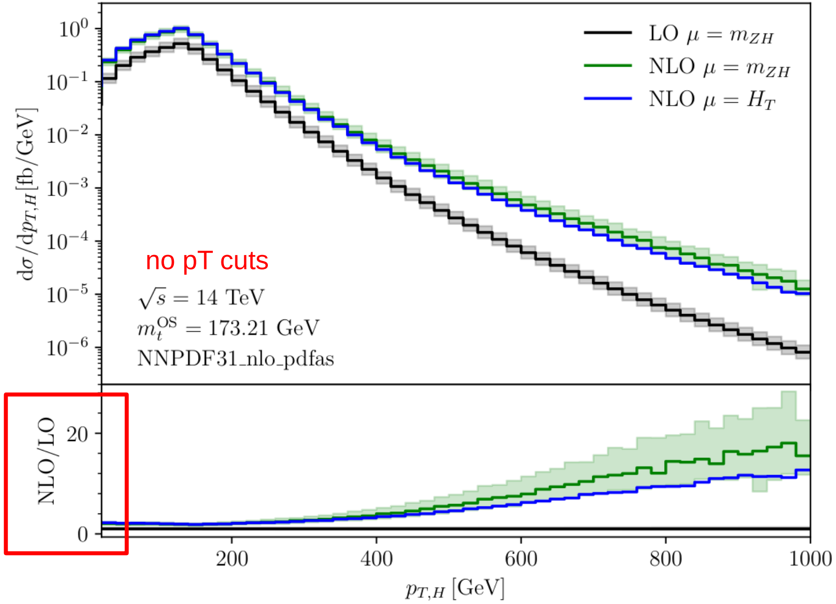
PDF suppressed

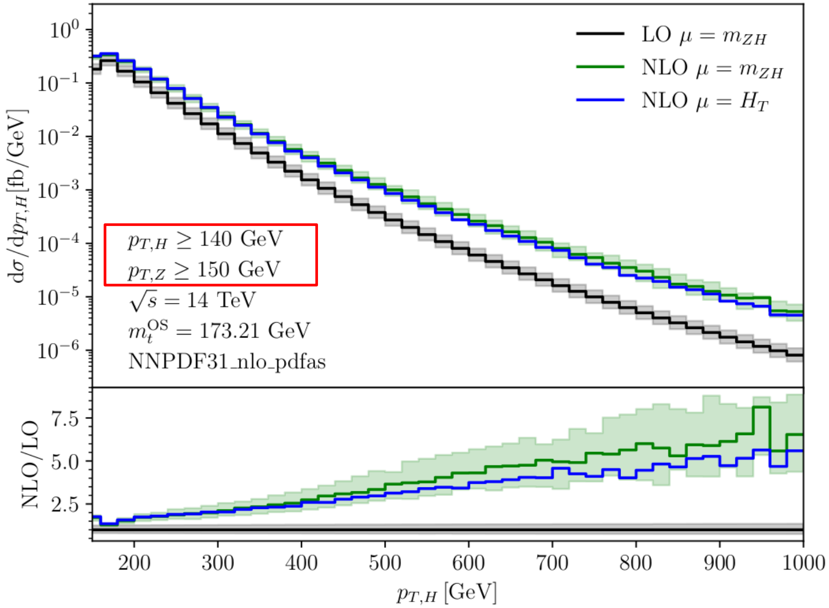


[Degrassi, Gröber, MV, Zhao - 2205.02769]

High-Energy Tails – pT Distributions

- Very large NLO corrections for $p_{T,H} > 400\,\mathrm{GeV}$
- Still K-factor of ~5 after pT cuts





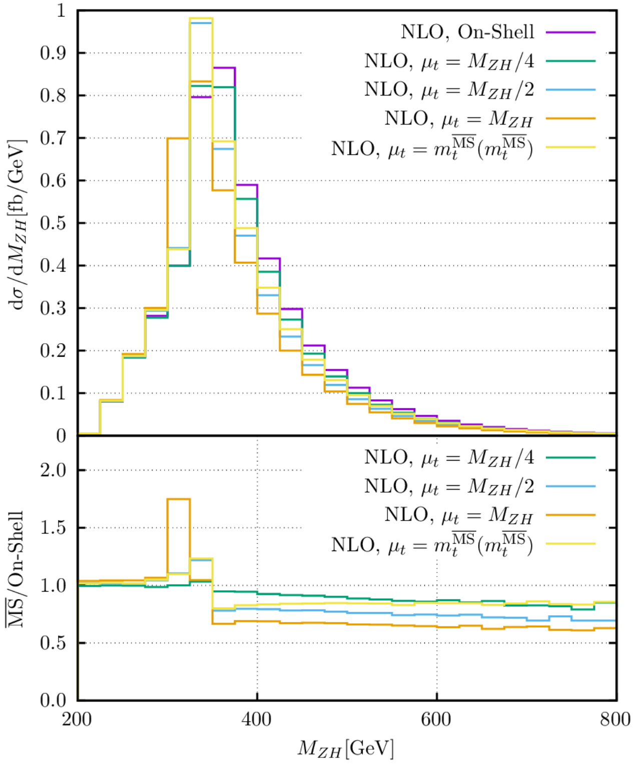
[Chen, Davies, Heinrich, Jones, Kerner, Mishima, Schlenk, Steinhauser - 2204.05225]

Top Mass Scheme Uncertainty

- Envelope of deviations of $\overline{\text{MS}}$ schemes wrt OS result
  Same method already used for HH production
  [Baglio et al. - 1811.05692, 2003.03227]
- Uncertainty sensitive to the binning of top-pair threshold peak

Bin Width [GeV]	LO	NLO
1	$64.01^{+15.6\%}_{-35.9\%}$	$118.6^{+17.2\%}_{-27.0\%}$
5	$64.01^{+15.3\%}_{-35.6\%}$	$118.6^{+14.7\%}_{-24.9\%}$
25	$64.01^{+14.0\%}_{-33.1\%}$	$118.6^{+10.9\%}_{-20.8\%}$
100	$64.01^{+2.0\%}_{-25.3\%}$	$118.6^{+0.6\%}_{-13.7\%}$
∞	$64.01^{+0\%}_{-23.1\%}$	$118.6^{+0\%}_{-12.9\%}$

Avoid overestimate of uncertainty



[Degrassi, Gröber, MV, Zhao - 2205.02769]

- Top-mass uncertainty ~ scale uncertainty
- Agreement with [Chen et al. - 2204.05225] for $M_{ZH} > 400\,\text{GeV}$

(Predictions for different schemes available only in this region for both papers)

Plans

- Update of inclusive prediction for fixed-order $gg \to ZH$ cross section
  Cross-checks in progress between [Chen, Davies, Heinrich, Jones, Kerner, Mishima, Schlenk, Steinhauser - 2204.05225]
  [Degrassi, Gröber, MV, Zhao - 2205.02769]
- Provide K-factors for single and double-differential distributions
- **Goal:** implementation of unified prediction in PowHeg
- **Bonus:** inclusion of BSM effects via anomalous couplings

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Thank you for your attention

Fixed-Order Predictions for $pp \to ZH$

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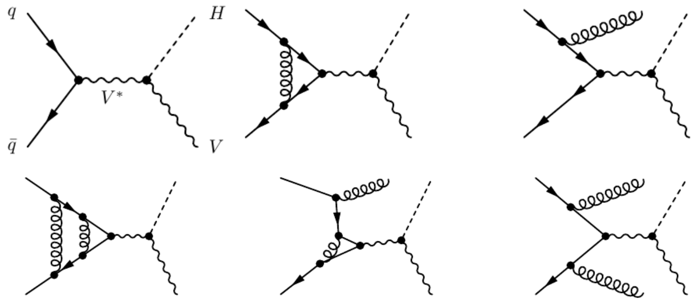
LO: quark-initiated tree-level contribution

QCD effects: mainly due to Drell-Yan (DY) production followed by $Z^* \to ZH$ decay

- **Drell-Yan**

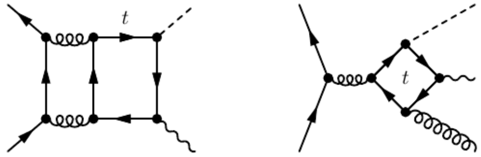


- Known through N3LO (+30% wrt LO)

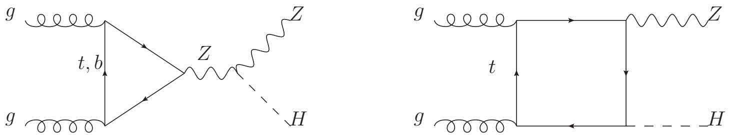
  [Han, Willenbrock ('91) ; Hamberg, van Neerven, Matsuura ('92) ; Brein, Djouadi, Harlander – 0307206; Baglio, Duhr, Mistlberger, Szafron - 2209.06138]

- **Non Drell-Yan - quark-initiated** O(1%) wrt LO

  [Brein, Harlander, Wiesemann, Zirke - 1111.0761]



- **Non Drell-Yan - gluon-initiated**



EW corrections: known through NLO (-(5-10%) wrt LO)

[Dittmaier et al. - 1211.5015]

$gg \to ZH$ @ NLO QCD – Inclusive Cross Section

[Wang, Xu, Xu, Yang - 2107.08206]

$\sqrt{s} = 13\text{TeV}$

$\mu_r = \mu_f$	σ^{gg}_{LO}	σ^{gg}_{NLO}	$\sigma^{\text{no } gg}_{pp\to ZH}$	$\sigma_{pp\to ZH}$	$\sigma^{gg, m_t\to\infty}_{\text{NLO}}$	$\sigma^{m_t\to\infty}_{pp\to ZH}$
$M_{ZH}/3$	73.56(7)	129.4(3)	784.0(7)	913.4(7)	133.6(6)	917.6(9)
M_{ZH}	51.03(5)	101.7(2)	781.1(7)	882.9(7)	106.0(4)	887.2(8)
$3M_{ZH}$	36.62(4)	80.4(2)	780.7(8)	861.1(8)	84.0(3)	864.8(9)

[Chen et al. - 2204.05225]

$\mu_r = \mu_f = M_{ZH}$

$\sqrt{s}$	LO [fb]	NLO [fb]
13 TeV	$52.42^{+25.5\%}_{-19.3\%}$	$103.8(3)^{+16.4\%}_{-13.9\%}$
13.6 TeV	$58.06^{+25.1\%}_{-19.0\%}$	$114.7(3)^{+16.2\%}_{-13.7\%}$
14 TeV	$61.96^{+24.9\%}_{-18.9\%}$	$122.2(3)^{+16.1\%}_{-13.6\%}$

- NLO corrections are the same size as LO

[Degrassi, Gröber, MV, Zhao - 2205.02769]

$\sqrt{s} = 13\text{TeV}$

$\mu_r = \mu_f = M_{ZH}/2$

Top-mass scheme	LO [fb]	$\sigma_{LO}/\sigma^{OS}_{LO}$	NLO [fb]	$\sigma_{NLO}/\sigma^{OS}_{NLO}$	$K = \sigma_{NLO}/\sigma_{LO}$
On-Shell	$64.01^{+27.2\%}_{-20.3\%}$	—	$118.6^{+16.7\%}_{-14.1\%}$	—	1.85
$\overline{\text{MS}}, \mu_t = M_{ZH}/4$	$59.40^{+27.1\%}_{-20.2\%}$	0.928	$113.3^{+17.4\%}_{-14.5\%}$	0.955	1.91
$\overline{\text{MS}}, \mu_t = m_t^{\overline{\text{MS}}}(m_t^{\overline{\text{MS}}})$	$57.95^{+26.9\%}_{-20.1\%}$	0.905	$111.7^{+17.7\%}_{-14.6\%}$	0.942	1.93
$\overline{\text{MS}}, \mu_t = M_{ZH}/2$	$54.22^{+26.8\%}_{-20.0\%}$	0.847	$107.9^{+18.4\%}_{-15.0\%}$	0.910	1.99
$\overline{\text{MS}}, \mu_t = M_{ZH}$	$49.23^{+26.6\%}_{-19.9\%}$	0.769	$103.3^{+19.6\%}_{-15.6\%}$	0.871	2.10

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- Scale uncertainties reduced by ~30% wrt LO

[Degrassi, Gröber, MV, Zhao - 2205.02769]

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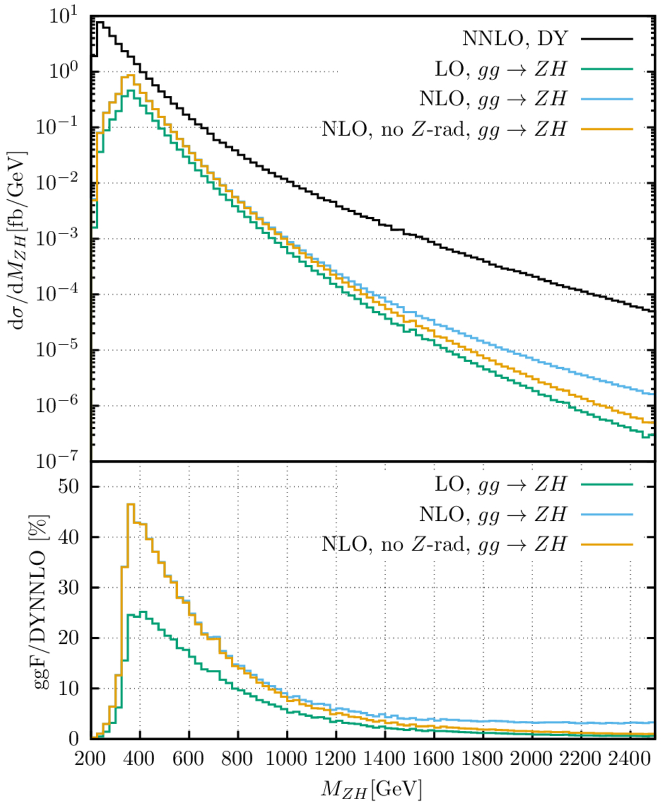
$gg \to ZH$ @ NLO vs Drell-Yan contribution

- $gg \to ZH$ is almost 50% of DY near $M_{ZH} \sim 2\, m_t$
- Because of Z-radiated diagrams the gg contribution falls off as rapidly as the DY one (ratio constant at ~ 2%)
- DY obtained using **vh@nnlo**
  [Harlander et al - 1802.04817]



[Degrassi, Gröber, MV, Zhao - 2205.02769]