Karlsruhe Institute of Technology

$gg \to ZH$: updated predictions at NLO QCD including SMEFT contributions

LHCHWG (2025) CERN

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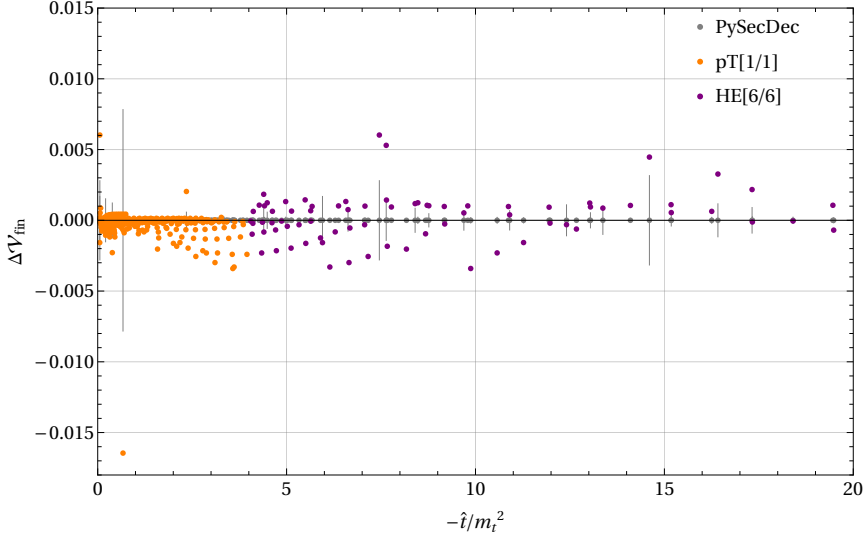
Introduction/Motivation

- See Dominik's Talk
- Want: POWHEG-code to be used by experimentalists and theorists
- SM POWHEG code ready, extend it to SMEFT
- High p_T-tail expected to be sensitive to new physics

Virtual Corrections and Real Radiation

- Computed by different groups with different methods:
  - Gröber et al. 22', Steinhauser et al 21':
    via Padé[1,1] transverse momentum expansion and Padé[6,6] high energy expansion
  - Heinrich, Jones, Steinhauser et al. 22':
    Exact result for specific phase-space points and $m_t^2 = 23/12\ m_H^2$
  - New: Steinhauser et al. 25'
    Deep expansions in high-energy region and around the forward limit
- Use Gröber et al. after assessing difference to numerical approach.
- Use GoSam-3.0 (Braun, Heinrich et al. 25') for real radiation

Comparision between Virtuals



$$\Delta\mathcal{V}_{\text{fin}} = \frac{\alpha_s}{4\pi}\frac{\left(\mathcal{V}_{\text{fin}G.} - \mathcal{V}_{\text{fin}H.}\right)}{\mathcal{B}}$$

Dominant Theory uncertainites

Top-Mass Scheme:

- Compute Top-Mass in OS scheme and in $\overline{\text{MS}}$ with $\mu_t = \{M_{ZH}, M_{ZH}/2, M_{ZH}/4\}$
- Conversion between on-shell and $\overline{\text{MS}}$ computed using CRunDec (Steinhauser et al 12')

Scale Uncertainty:

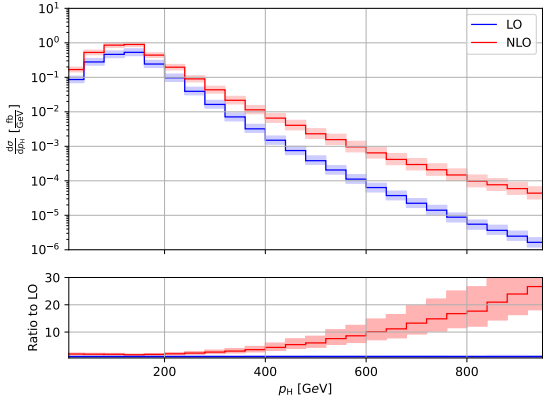
- Use scale: $\mu_F = \mu_R = M_{ZH}/2$
- Use 7-point variation by $\{1/2, 1, 2\}$
- Use PDF4LHC21_40_pdfas

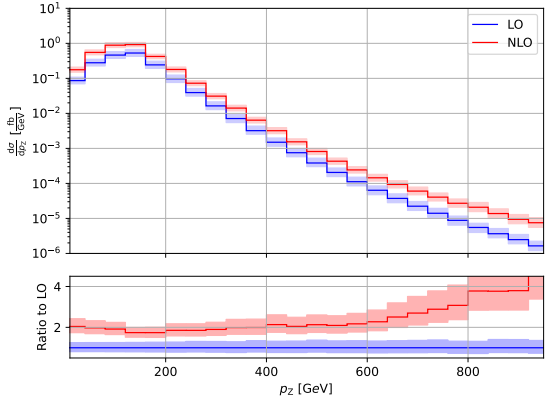
Cross Section Results

$\sqrt{S}$ [TeV]	m_H [GeV]	σ_{LO} [fb]	σ_{NLO} [fb]
13	124.6	$64.3^{+27+0\%}_{-20-23\%}$	$119.0^{+17+0\%}_{-14-13\%}$
13	125.0	$64.0^{+27+0\%}_{-20-23\%}$	$118.4^{+17+0\%}_{-14-13\%}$
13	126.0	$63.3^{+27+0\%}_{-20-24\%}$	$117.1^{+16+0\%}_{-14-13\%}$
13.6	124.6	$70.9^{+26+0\%}_{-20-24\%}$	$131.1^{+16+0\%}_{-14-13\%}$
13.6	125.0	$70.6^{+26+0\%}_{-20-24\%}$	$130.5^{+16+0\%}_{-14-13\%}$
13.6	126.0	$69.8^{+26+0\%}_{-20-24\%}$	$129.1^{+16+0\%}_{-14-13\%}$
14	124.6	$75.5^{+26+0\%}_{-20-24\%}$	$139.5^{+16+0\%}_{-14-14\%}$
14	125.0	$75.2^{+26+0\%}_{-20-24\%}$	$138.9^{+16+0\%}_{-14-13\%}$
14	126.0	$74.4^{+26+0\%}_{-20-24\%}$	$137.3^{+16+0\%}_{-14-14\%}$

- Uncertainties are Scale + Top-mass-scheme
- Top-mass-scheme uncertainties are asymmetric and substantial
- Cross section decreases with higher Higgs mass and increases with higher energies.

Results Higgs and Z Tranverse Momentum





SMEFT

- Include Leading SMEFT Operators:

$$\mathcal{O}_{H\Box} = \left(H^\dagger H\right) \Box \left(H^\dagger H\right), \quad \mathcal{O}_{HD} = \left(H^\dagger D_\mu H\right) \left(H^\dagger D^\mu H\right)^*$$

$$\mathcal{O}_{HQ}^{(1)} = \left(iH^\dagger \overleftrightarrow{D}_\mu H\right) \left(\bar{Q}_L \gamma^\mu Q_L\right), \quad \mathcal{O}_{HQ}^{(3)} = \left(iH^\dagger \overleftrightarrow{D}^I_\mu H\right) \left(\bar{Q}_L \gamma^\mu \tau^I Q_L\right),$$

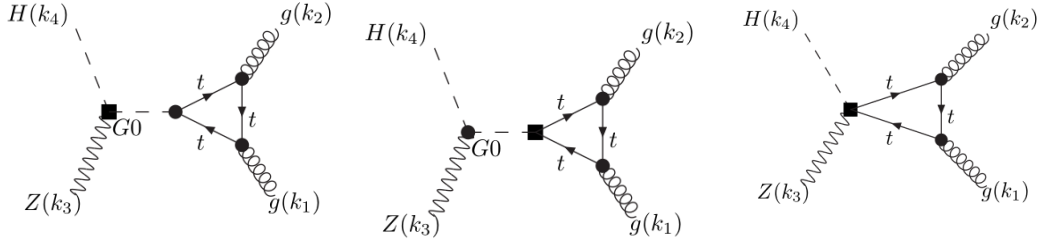
$$\mathcal{O}_{Ht} = \left(i\, H^\dagger \overleftrightarrow{D}_\mu H\right) \left(\bar{t}_R \gamma^\mu t_R\right)$$

$$\mathcal{O}_{HG} = H^\dagger H G_{\mu\nu} G^{\mu\nu}$$

- Use GoSam-3.0 (Braun, Heinrich et al. 25') for real radiation

Triangles

- Operators of the form $\left(i H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{Q}\gamma^\mu Q\right)$, $\left(iH^\dagger \overleftrightarrow{D}^I_\mu H\right)\left(\bar{Q}\gamma^\mu \tau^I Q\right)$ cancel in triangles (Rossia, Thomas, Vryonidou 23'):



- Thus no new diagrams or Lorentz structures need to be computed
- Only new diagrams stem from $\mathcal{O}_{HG} = H^\dagger H G_{\mu\nu} G^{\mu\nu}$

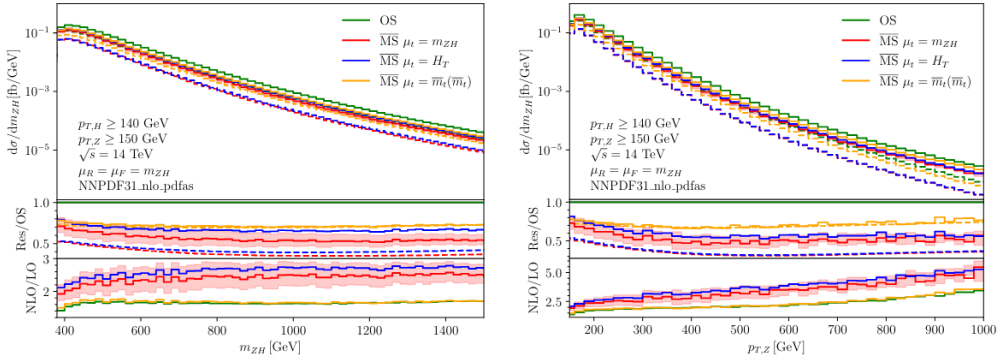
Conclusion

- Implemented full NLO QCD corrections to $gg \to ZH$ with analytic top-mass dependence in Powheg
- Allows study of top mass scheme uncertainty
- Top-mass-scheme uncertainties has substantial impact
- Allows study of SMEFT operators

Other Uncertainties

- α_S: Vary $\alpha_s(m_Z) = 0.1180$ by ± 0.001. Note they are still taken from the PDFs, but now from one where $\alpha_s(m_Z) = 0.1181$ or $\alpha_s(m_Z) = 0.1179$
  NLO: $\Delta_{\alpha_s} = \pm 1.8\%$
- PDF: Compute all Hessian PDF sets and use: $\delta^{\mathrm{PDF}}\sigma = \sqrt{\sum_{k=1}^{40}(\sigma^{(k)} - \sigma^{(0)})^2}$
  NLO: $\Delta_{\mathrm{PDF}} = \pm 2.3\%$

Distributions



Taken from Heinrich, Jones, Steinhauser et al. 22'

- $A_i^{(0)} \sim m_t^2 f_i(s,t) \log^2\left[\frac{m_t^2}{s}\right]$ and $A_i^{(1)} \sim \frac{C_A - C_F}{6} A_i^{(0)} \log^2\left[\frac{m_t^2}{s}\right]$