

ZH production in gluon fusion at NLO QCD with SMEFT effects

High Precision for Hard Processes

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8. October 2026

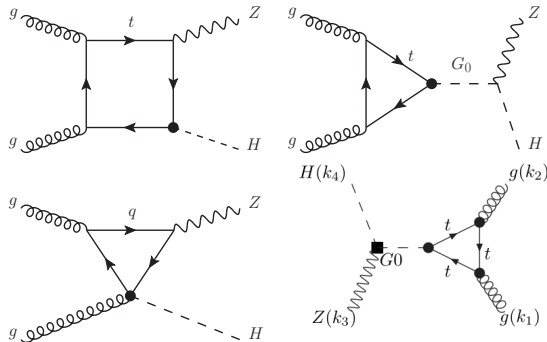
Introduction/Motivation

Why ZH production?

- Third largest contribution to H production cross section
- Study of $H \rightarrow b\bar{b}$

Why SMEFT?

- Can study anomalous Higgs-Fermion interactions
- Can study anomalous Higgs-Gauge-Boson interactions

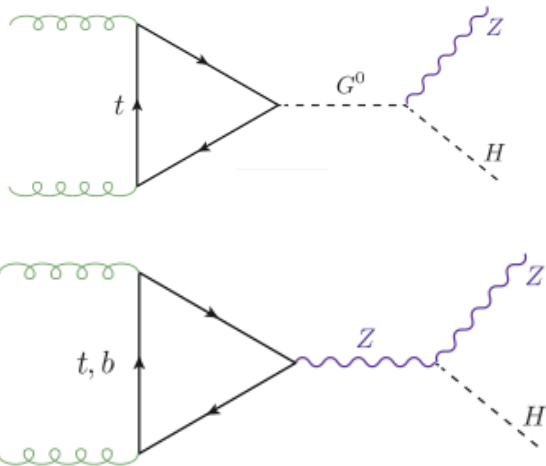


History

- $q\bar{q} \rightarrow ZH$ known to:
 - N³LO QCD Baglio, C. Duhr, B. Mistlberger and R. Szafron 22' for Drell-Yan
 - NNLO QCD O. Brein, A. Djouadi and R. Harlander 03'
 - NNLO QCD G. Ferrera, M. Grazzini and F. Tramontano, 15' and J. M. Campbell, R. K. Ellis and C. Williams 16' fully differential
- $gg \rightarrow ZH$ known to NLO QCD:
 - L. Altenkamp, S. Dittmaier, R. V. Harlander, H. Rzehak and T. J. E. Zirke 13' with $m_t \rightarrow \infty$
 - J. Davies, G. Mishima and M. Steinhauser 11' in high-energy limit
 - L. Chen, G. Heinrich, S. P. Jones, M. Kerner, J. Klappert and J. Schlenk 20' numerically with full top mass dependence
 - L. Alasfar, G. Degrossi, P. P. Giardino, R. Gröber and M. Vitti 21' analytically via expansion in small p_T
 - G. Degrossi, R. Gröber, M. Vitti and X. Zhao 22' combining small p_T and high-energy expansion
 - J. Davies, D. Graug, K. Schönwald, M. Steinhauser, D. Stremmer, M. Vitti 25' by deep expansion in high-energy region and forward limit
 - J. Davies, D. Graug, K. Schönwald, M. Steinhauser, D. Stremmer 25' at NNLO QCD with $m_t \rightarrow \infty$
 - J. Davies, K. Schönwald, M. Steinhauser, D. Stremmer 26' published POWHEG Code for NLO QCD

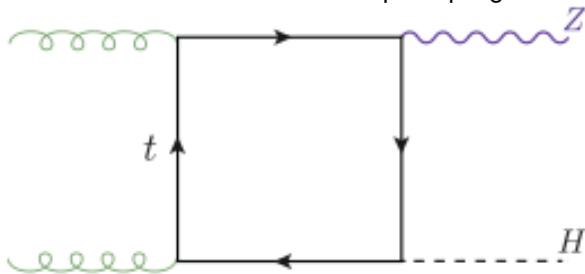
Born Triangles

- Can have triangles with either Z or G^0 propagators
- Using Landau gauge $\xi_Z = 0$: Propagator of Z : $-g^{\mu\nu} + \frac{k^\mu k^\nu}{k^2} = \sum \epsilon^\mu \epsilon^{\nu*}$
- Z -propagator diagrams vanish due to Landau-Yang theorem



Born Box

Furry: diagrams with uneven number of vector-fermion-loop-couplings vanish $\Rightarrow$ only axial γ^5 survives



Virtuals

We will focus on two computations of the virtuals:

L. Chen, G. Heinrich, S. P. Jones et al. 20'

- Generate amplitude
- Reduce to master integrals
- Use PySecDec with $m_H^2/m_t^2 = 12/23$ to evaluate phase-space points

Advantage: Exact result for specific phase space points

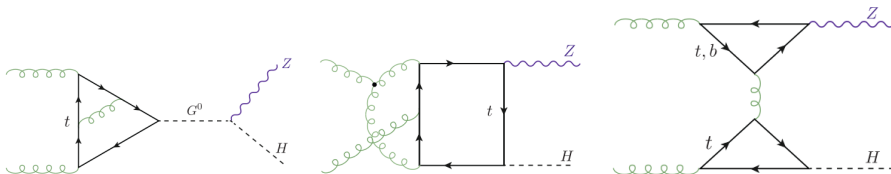
Disadvantage: Top- and Higgs mass fixed

G. Degrandi, R. Gröber et al. 22'

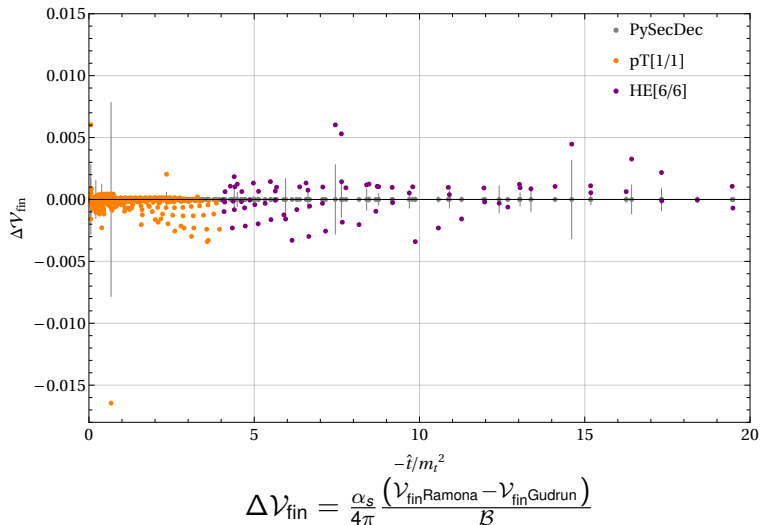
- Combine small $p_{T,Z}/s \ll 1$ and high energy expansion $s \gg m_t^2$ for Boxes
- Evaluate triangle/double triangles analytically.

Advantage: Fast evaluation over entire phase space, allows for top-mass variation

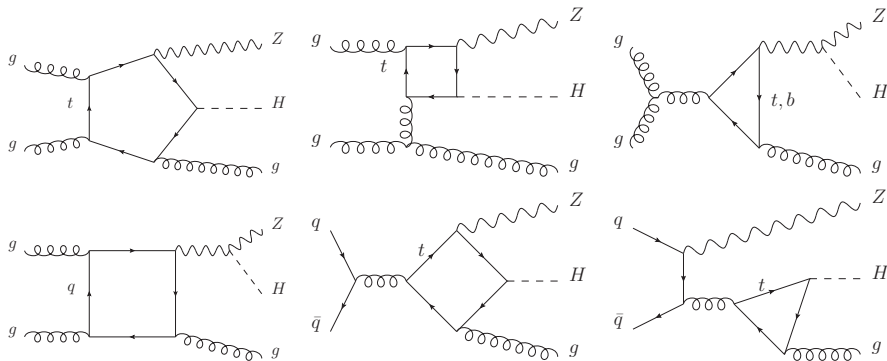
Disadvantage: Only approximation



Comparison between Virtuals in the SM



Real corrections



Can easily be computed with GoSam [J. Braun, BC, G. Heinrich, M. Höfer, S.P. Jones et al. 25'](#)

Results Higgs and Z Transverse Momentum

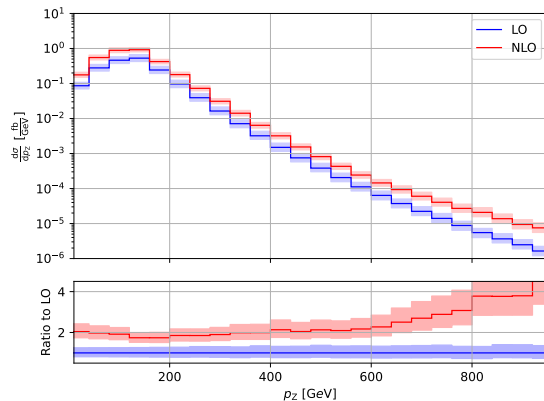
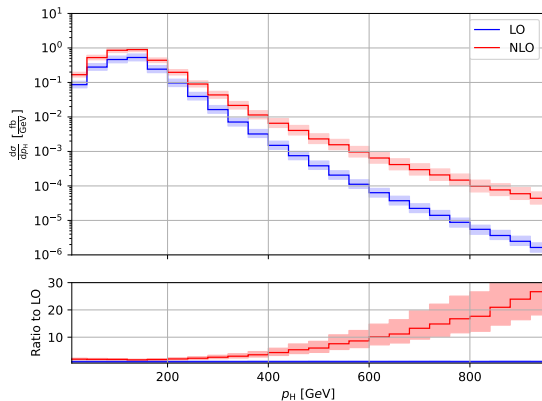


Figure taken from [BC, R. Gröber, G. Heinrich et. al 25'](#)

SMEFT Operators

Modification to Top Yukawa

$$\mathcal{O}_{tH} = H^\dagger H (\bar{Q}_L \tilde{H} t_R) + \text{h.c.}$$

Modification to Quark-Gauge-Higgs

$$\begin{aligned}\mathcal{O}_{Ht} &= (iH^\dagger \overleftrightarrow{D}_\mu H) (\bar{t}_R \gamma^\mu t_R), \\ \mathcal{O}_{HQ}^{(1)} &= (iH^\dagger \overleftrightarrow{D}_\mu H) (\bar{Q}_L \gamma^\mu Q_L), \\ \mathcal{O}_{HQ}^{(3)} &= (iH^\dagger \overleftrightarrow{D}_\mu^I H) (\bar{Q}_L \tau^I \gamma^\mu Q_L)\end{aligned}$$

Higgs Kinetic Terms

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

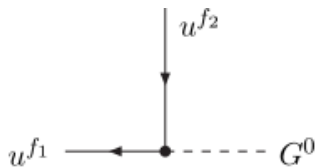
Loop Induced Operators

$$\begin{aligned}\mathcal{O}_{tG} &= \bar{Q}_L \sigma^{\mu\nu} T^a G_{\mu\nu} \tilde{H} t_R + \text{h.c.} \\ \mathcal{O}_{HG} &= H^\dagger H G_{\mu\nu} G^{\mu\nu}\end{aligned}$$

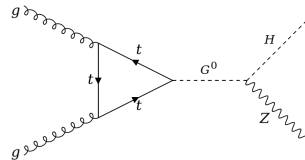
Light Quark Operators

$$\begin{aligned}\mathcal{O}_{Hu} &= (iH^\dagger \overleftrightarrow{D}_\mu H) (\bar{u}_R \gamma^\mu u_R), \\ \mathcal{O}_{Hd} &= (iH^\dagger \overleftrightarrow{D}_\mu H) (\bar{d}_R \gamma^\mu d_R), \\ \mathcal{O}_{Hq}^{(1)} &= (iH^\dagger \overleftrightarrow{D}_\mu H) (\bar{q}_L \gamma^\mu q_L), \\ \mathcal{O}_{Hq}^{(3)} &= (iH^\dagger \overleftrightarrow{D}_\mu^I H) (\bar{q}_L \tau^I \gamma^\mu q_L)\end{aligned}$$

Computation of Born



$$\begin{aligned}
 & -\frac{1}{v}\delta_{f_1 f_2} m_{u_{f_1}} \gamma^5 + \frac{v}{4}\delta_{f_1 f_2} C^{\phi D} m_{u_{f_1}} \gamma^5 \\
 & -v \boxed{\not{p}_3 P_L} C^{\phi q1} + v \boxed{\not{p}_3 P_L} C^{\phi q3} \\
 & -v \boxed{\not{p}_3 P_R} C^{\phi u}
 \end{aligned}$$



1

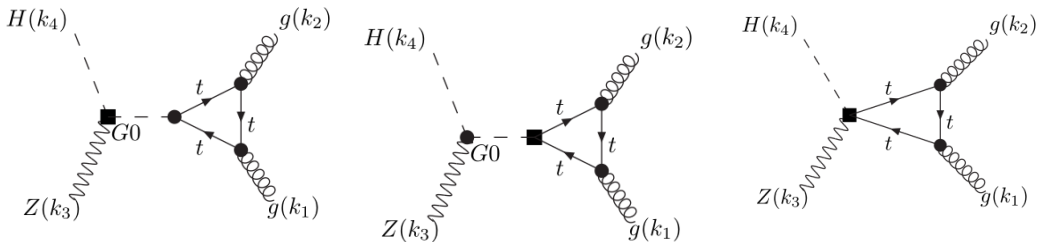
¹FeynRules taken from: [A. Dedes, W. Materkowska, M. Paraskevas, J. Rosiek, K. Suxho 17'](#)

Computation of Born

- Already have analytical SM Born
- SMEFT can introduce new Lorentz structures (in $q\bar{q}G^0$ -vertices) and new vertices.

Cancellation of Triangles

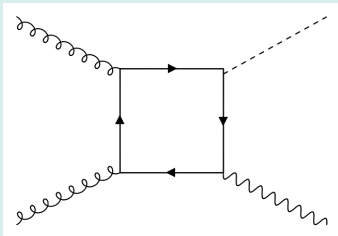
Operators $\mathcal{O}_{Ht}$, $\mathcal{O}_{HQ}^{(1)}$ and $\mathcal{O}_{HQ}^{(3)}$ cancel in triangles ([Rossia, Thomas, Vryonidou 23'](#)):



- Thus no new diagrams or Lorentz structures need to be computed

Computation of the Born Amplitude

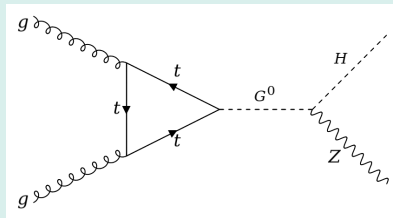
Modification of Box Diagrams



Modifications $Ht\bar{t}$ and $Zt\bar{t}$, thus:

$$1 + \left[C_{H\Box} - \frac{1}{2} C_{HD} - C_{HQ}^{(1)} + C_{Ht} + C_{HQ}^{(3)} - C_{tH} \frac{v}{m_t \sqrt{2}} \right] \frac{v^2}{\Lambda^2}$$

Modification of Triangle Diagrams



$$1 + C_{H\Box} \frac{v^2}{\Lambda^2}$$

Virtuals in SMEFT

- We have our analytical virtual. How to obtain SMEFT?
- We only look at QCD corrections!
- No new insertion of our SMEFT operators possible!

Modification of Boxes

Get same modification as in Born diagrams:

$$\square_{\text{SMEFT}} = \square_{\text{SM}} \left(1 + \left[C_{H\square} - \frac{1}{2} C_{HD} - C_{HQ}^{(1)} + C_{Ht} + C_{HQ}^{(3)} - C_{tH} \frac{v}{m_t \sqrt{2}} \right] \frac{v^2}{\Lambda^2} \right)$$

Modification of Triangles

Get same modification as in Born diagrams: $\triangle_{\text{SMEFT}} = \triangle_{\text{SM}} \left(1 + C_{H\square} \frac{v^2}{\Lambda^2} \right)$

Virtuals in SMEFT

Modification of Double-Triangles

- double-triangles with only top-loops:

$$\Delta_{\text{SMEFT},t} = \Delta_{\text{SM},t} \left(1 + \left[C_{H\Box} - \frac{1}{2} C_{HD} - C_{HQ}^{(1)} + C_{Ht} + C_{HQ}^{(3)} - C_{tH} \frac{v}{m_t \sqrt{2}} \right] \frac{v^2}{\Lambda^2} \right)$$

- double-triangles with a bottom-loop:

$$\Delta_{\text{SMEFT},b} = \Delta_{\text{SM},b} \left(1 + \left[C_{H\Box} - \frac{1}{2} C_{HD} - \frac{v}{\sqrt{2} m_t} C_{tH} - C_{Hb} + C_{HQ}^{(1)} + C_{HQ}^{(3)} \right] \frac{v^2}{\Lambda^2} \right)$$

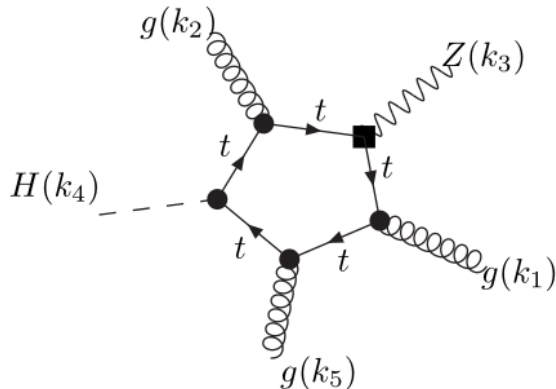
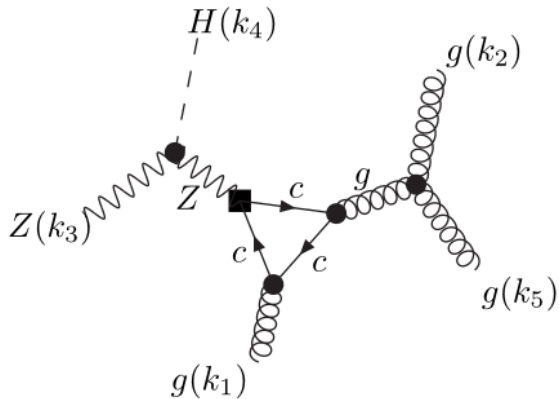
- double-triangles with one light-quark loop:

$$\Delta_{\text{SMEFT},q} = \Delta_{\text{SM},b} \left(\left[-C_{Hu} - C_{Hd} - C_{Hc} - C_{Hs} + 2C_{Hq1}^{(1)} + 2C_{Hq2}^{(1)} \right] \frac{v^2}{\Lambda^2} \right).$$

$\Delta_{\text{SM},b}$ = double-triangles with one top and one bottom loop

$\Delta_{\text{SM},t}$ = double-triangles with only top loops

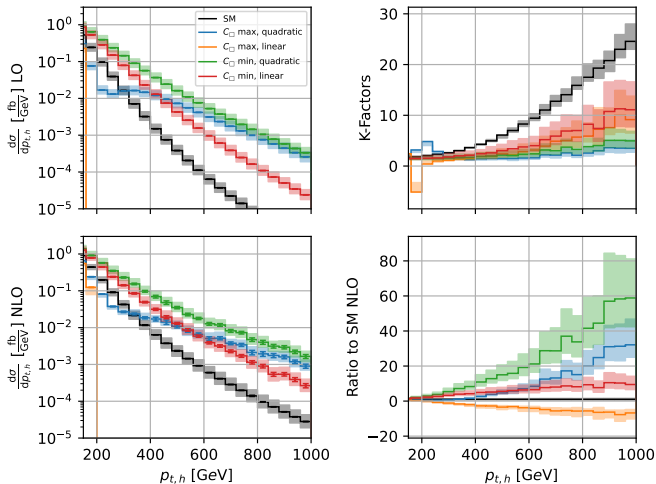
Real Corrections in SMEFT



Can be implemented by GoSam 3.0

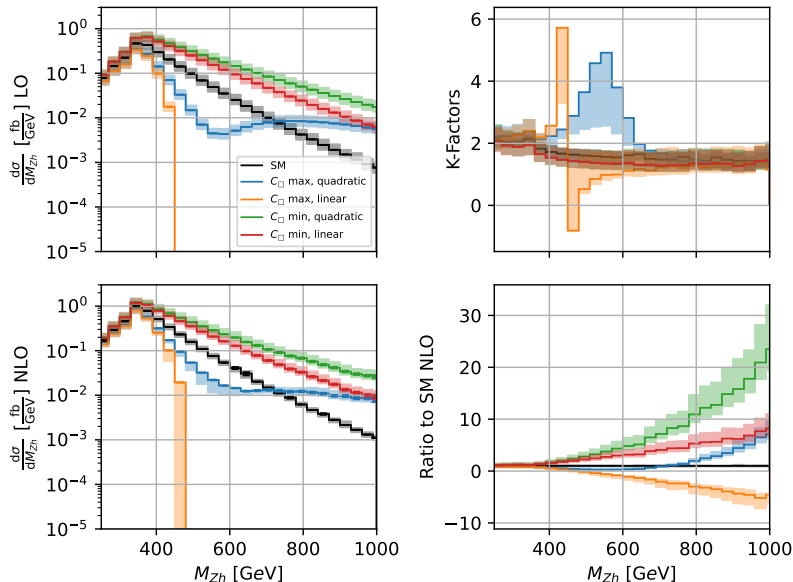
Varying the Box coefficient; Higgs Transverse Momentum

- Vary: $\square_{\text{SMEFT}} = \square_{\text{SM}} \left(1 + \left[C_{H\square} - \frac{1}{2} C_{HD} - C_{HQ}^{(1)} + C_{Ht} + C_{HQ}^{(3)} - C_{tH} \frac{v}{m_t \sqrt{2}} \right] \frac{v^2}{\Lambda^2} \right)$ by $\{(1.9, -1.7), (-0.85, 1.49), (-2.8, 2.9), (0.9, -1), (-4.4, 2.8)\}$



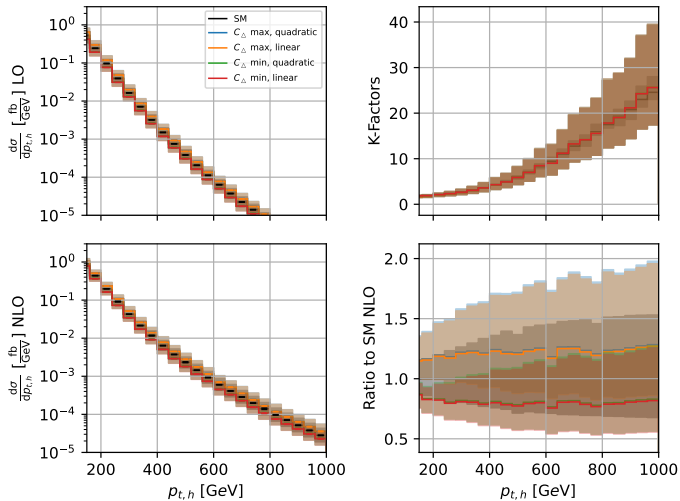
- Bounds are taken from [Hoeve et al. 25'](#)
- High p_T -tail very sensitive to SMEFT
- K-factors vary a lot
- Linear truncation order (orange) can turn negative!

Varying the Box coefficient; Invariant Mass



Varying the Triangle Coefficient

Vary $\Delta_{\text{SMEFT}} = \Delta_{\text{SM}} \left(1 + C_{H\Box} \frac{v^2}{\Lambda^2}\right)$ by $\{(1.8, -1.74)\}$



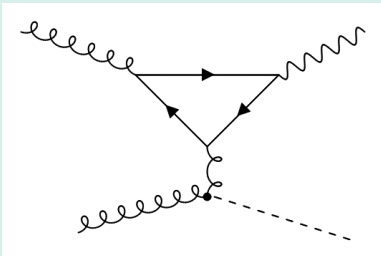
Virtuals in SMEFT: Loop Induced Operators

One or two-loop?

The operators are loop-induced in renormalisable weakly coupled UV theories, and thus these are actually two-loop diagrams.

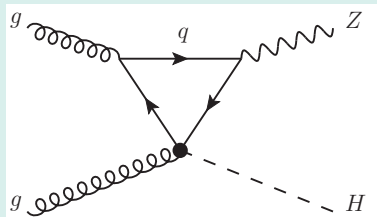
Higgs-gluon couplings

- $\mathcal{O}_{HG} = H^\dagger H G_{\mu\nu} G^{\mu\nu}$
- "Integrate out" one triangle



Chromomagnetic Operators

- $\mathcal{O}_{tG} = \bar{Q}_L \sigma^{\mu\nu} T^a G_{\mu\nu} \tilde{H} t_R + \text{h.c.}$
- Will modify quark-gluon couplings in Born-like diagrams
- Introduces new $\bar{q}qHg$ - vertices



Gamma5 in D dimension

- in D dimension cannot have $\{\gamma^\mu, \gamma^5\} = 0$ & cyclicity of trace
- Use BMHV/Kreimer scheme

What is BMHV scheme

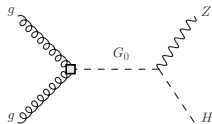
- Give up anticommutativity.
- Can break BRST symmetries

What is Kreimer scheme

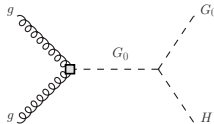
- Give up cyclicity of the trace
- Choose unambiguous reading point
- Choose SMEFT vertex as reading point

BMHV and Symmetries

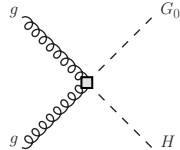
- BMHV result is gauge dependent
- Result violates Slavnov–Taylor identity $ip_\mu \mathcal{M}(Z^\mu(p), \phi_i(q_i)) - m_Z \mathcal{M}(G_0(p), \phi_i(q_i)) = 0$,
- Introduce two new symmetry restoring operators
 - $\mathcal{O}_{ct_1} \sim C_{tG} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a G^0$, $\mathcal{O}_{ct_2} \sim C_{tG} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a G^0 h$



(a)



(b)



(c)

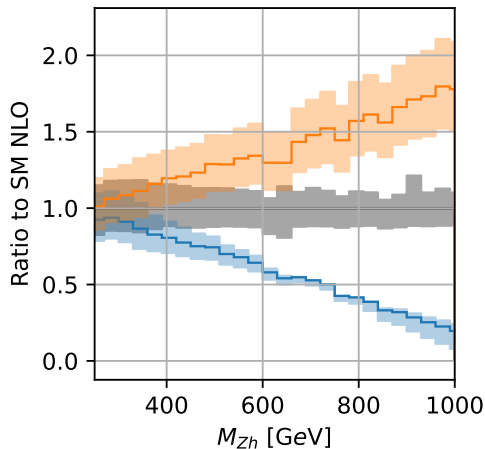
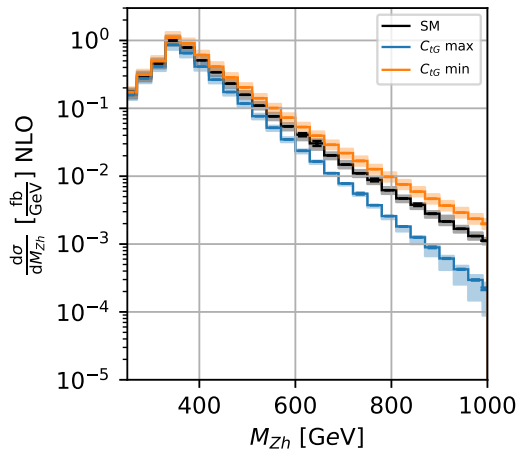
This restores the Slavnov–Taylor identities!

BMHV and Kreimer

- Computed BMHV and Kreimer scheme
- Checked that BMHV (with counterterms) agrees with Kreimer
- Cross-checked analytical implementation with GoSam

Varying the Chromomagnetic Operator

Vary C_{UG} by $\{-1, 1\}$



Top Mass Scheme Uncertainty

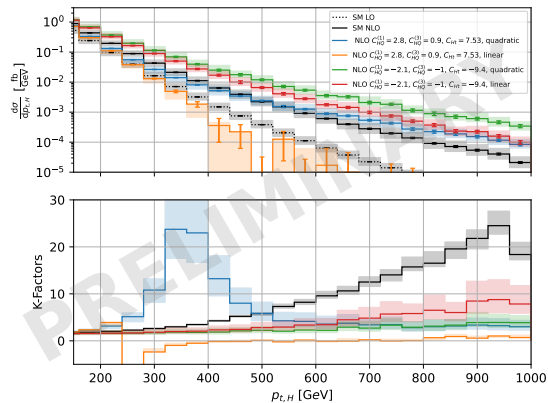
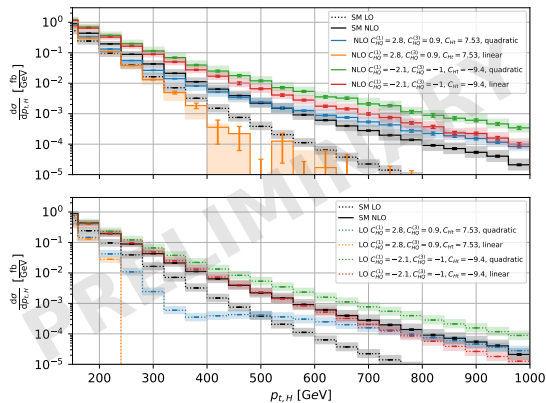
σ_{NLO} [fb]	max		min	
	quadratic	linear	quadratic	linear
SM	$130.5^{+16+0\%}_{-14-13\%}$			
Box ($C_{\Box}$)	$95.3^{+8+0\%}_{-14-9\%}$	$60.7^{+2+0\%}_{-13-22\%}$	$246^{+26+0\%}_{-14-7\%}$	$206^{+24+0\%}_{-14-12\%}$
Triangle (C_{Δ})	$152^{+19+0\%}_{-14-15\%}$	$151^{+19+0\%}_{-14-15\%}$	$113^{+13+0\%}_{-14-12\%}$	$112^{+13+0\%}_{-14-12\%}$
Chromomagnetic (C_{tG})	$108^{+15+0\%}_{-13-10\%}$		$153^{+17+0\%}_{-14-16\%}$	

- Format: $\sigma \pm \Delta_{\text{scale}}[\%] \pm \Delta_{m_t}[\%]$; “max”/“min” refer to the coefficients, not the cross-section
- Scale: seven-point envelope of μ_R, μ_F around $m_{ZH}/2$
- Top mass: envelope of on-shell and $\overline{\text{MS}}$ with $\mu_t \in \{m_{ZH}/4, m_{ZH}/2, m_{ZH}\}$
- C_{tG} : linear and quadratic truncations coincide

Conclusion

- Implemented SMEFT dimension-6 operators combined with NLO QCD corrections to $gg \rightarrow ZH$
- Allows study of SMEFT operators at linear and quadratic truncation order
- K-factors in the presence of SMEFT operators can be smaller than in the SM in the high- p_T region
- BMHV scheme breaks symmetries and needs counterterms
- Scale and top-mass scheme uncertainties vary a lot.
- Code will be publicly available.

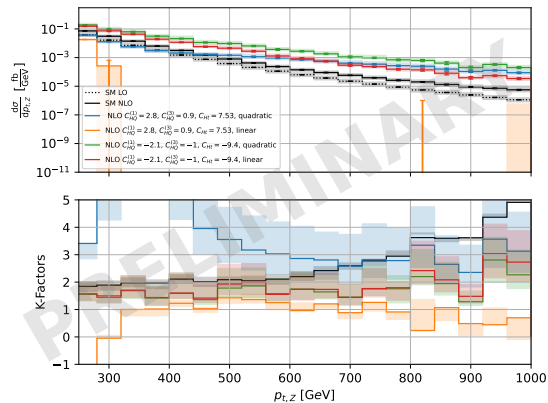
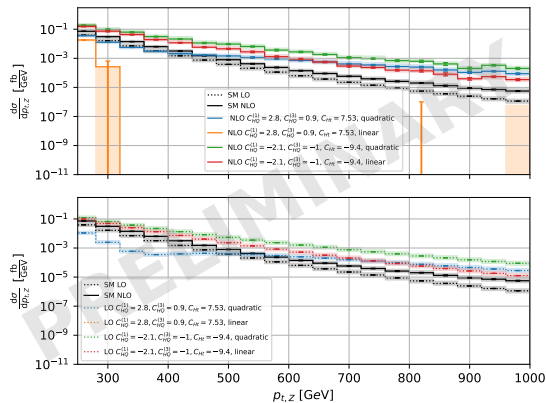
PRELIMINARY Results: Higgs Transverse Momentum



- Bounds are taken from [Hoeve, Mantani, Rojo, Rossia, Vryonidou 25'](#)
- High p_T -tail very sensitive to SMEFT
- K-factors vary a lot

- Linear truncation order (orange) can turn negative!
- SMEFT NLO can be mistaken for SM LO

PRELIMINARY Results: Z Transverse Momentum



- Bounds are taken from Hoeve, Mantani, Rojo, Rossia, Vryonidou 25'
- High p_T -tail very sensitive to SMEFT
- K-factors vary a lot

- Linear truncation order (orange) can turn negative!
- SMEFT NLO can be mistaken for SM LO

Other Wilson Coefficients

