SMEFTatNLO

SMEFT event generation exercise

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MG5: NLO mode

Similar but different from LO mode

```
MG5_aMC> tutorial aMCatNLO
MG5_aMC> generate p p > t t~ [QCD]
```

- `[QCD]`: requests NLO process generation (compatible models only!)
- Does not automatically compute cross section & generate events

`MG5_aMC> bin/madevent` ⇒ `MG5_aMC> bin/aMCatNLO` *different executable*

Fixed Order (FO)

```
MG5_aMC> launch NLO --name=MyRun_FO
```

- Only calculate cross sections & histograms (dedicated `FORTRAN` code)

NLO + PS

```
MG5_aMC> launch aMC@NLO --name=MyRun_NLOPS
```

- Generate events & match to parton shower via MC@NLO (`hepmc`)
- `WARNING`: NLO generated events are unphysical until showered
    - NLO calculation includes real-emission diagrams
    - Parton shower simulates many emissions ⇒ double-counting

MG5: NLO mode

Try generating NLO process

```
MG5_aMC> generate p p > t t~ [QCD]
```

- Check `run_card.dat`: not exactly the same
- Compare LO & NLO cross sections (`NLO` ⇔ `LO` in `launch` command)

```
MG5_aMC> launch LO --name=MyRun_FO_LO
```

- Decay syntax not available ✗

```
MG5_aMC> generate … [QCD], z > e+ e-
```

Running parton shower: shower_card.dat

- `run_card.dat`: set `PYTHIA8 = parton_shower`
- `pythia8_card.dat` (LO) ⇒ `shower_card.dat` (NLO)
    - `nsplit_jobs = n`: parallelise shower over n cores (e.g 4)
    - Higgs decay syntax modified
    - Check examples

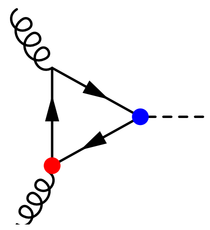
```
DM_1 = 25:onMode = off
DM_2 = 25:onIfMatch = 5 -5
```

Results in `Events/` as usual (`summary.txt` for cross section)

SMEFT@NLO

NLO computations for SMEFT: very active field

- Non-universal K-factors in EFT space ⇔ new information at NLO
- Loop-induced sensitivity
- Control theoretical uncertainties
- Experimental interest in higher precision for SMEFT analyses/interpretations



Challenge: many processes x many operators

- LO ⇒ NLO = more cross-talk/operators/complexity
- Automated tools for fixed-order/NLO+PS are essential to the LHC programme

SMEFT@NLO *[Degrande et al.; arXiv:2008.11743]*
http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

- UFO model for `MadGraph5_aMC@NLO`
- Process-independent implementation: SMEFT in top-specific flavor limit

http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

Standard Model Effective Theory at One-Loop in QCD

Céline Degrande, Gauthier Durieux, Fabio Maltoni, Ken Mimasu, Eleni Vryonidou & Cen Zhang, arXiv:2008.11743

The implementation is based on the Warsaw basis of dimension-six SMEFT operators, after canonical normalization. Electroweak input parameters are taken to be G_F, M_Z, M_W. The CKM matrix is approximated as a unit matrix, and a $U(2)_q \times U(2)_u \times U(3)_d \times (U(1)_l \times U(1)_e)^3$ flavor symmetry is enforced. It forbids all fermion masses and Yukawa couplings except that only of the top quark. The model therefore implements the five-flavor scheme for PDFs.

A new coupling order, `NP=2`, is assigned to SMEFT interactions. The cutoff scale `Lambda` takes a default value of 1 TeV^{-2} and can be modified along with the Wilson coefficients in the `param_card`. Operators definitions, normalisations and coefficient names in the UFO model are specified in definitions.pdf. The notations and normalizations of top-quark operator coefficients comply with the LHC TOP WG standards of 1802.07237. Note however that the flavor symmetry enforced here is slightly more restrictive than the baseline assumption there (see the dim6top page for more information). This model has been validated at tree level against the `dim6top` implementation (see 1906.12310 and the comparison details).

Current implementation

UFO model: SMEFTatNLO_v1.0.tar.gz

The current implementation imposes CP conservation. In the quark sector, it focuses primarily on top-quark interactions. The light-quark current operator, qqHDH, uuHDH, ddHDH, with coefficients `cpq3i`, `cpqMi`, `cpu`, `cpd` are however included. The triple-gluon operator, with coefficient `cG`, is currently not available (see the loop-capable GGG implementation). Vertices including more than four scalars or four leptons are not included. Scalar and tensor `QQll` operators, with coefficients `ctlS3`, `ctlT3`, and `cblS3`, break our flavor symmetry assumption and are not available for one-loop computations. Top-quark flavor-changing interactions, not compatible with the imposed flavor symmetry, are not included (see the loop-capable TopFCNC implementation).

Unlike prescribed by the LHC TOP WG, the top quark chromomagnetic-dipole operator coefficient `ctG` is normalized with a factor of the strong coupling, g_S. This normalization factor temporarily ensures compatibility with the 2.X.X series of MadGraph5_aMC@NLO but may be dropped in the future. As with every other appearance of this coupling in MadGraph5_aMC@NLO, its value is renormalisation-group evolved to the QCD renormalization scale (set in the run_card).

```
MG5_aMC>import model SMEFTatNLO
MG5_aMC>generate p p > t t~ NP=2 [QCD]
MG5_aMC>output
MG5_aMC>launch
```

'QCD' loops

coloured particles, strong coupling or 4-fermion couplings

support: smeftatnlo-dev@cern.ch

What's in the box?

'Warsaw' basis

[Grzadkowski et al.; JHEP 1010 (2010) 085]

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
~~$Q_{\widetilde G}$~~	~~$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$~~	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
~~$Q_{\widetilde W}$~~	~~$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$~~				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
~~$Q_{\varphi\widetilde G}$~~	~~$\varphi^\dagger\varphi\,\widetilde G^A_{\mu\nu}G^{A\mu\nu}$~~	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
~~$Q_{\varphi\widetilde W}$~~	~~$\varphi^\dagger\varphi\,\widetilde W^I_{\mu\nu}W^{I\mu\nu}$~~	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
~~$Q_{\varphi\widetilde B}$~~	~~$\varphi^\dagger\varphi\,\widetilde B_{\mu\nu}B^{\mu\nu}$~~	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
~~$Q_{\varphi\widetilde WB}$~~	~~$\varphi^\dagger\tau^I\varphi\,\widetilde W^I_{\mu\nu}B^{\mu\nu}$~~	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	~~Q_{duq}~~	~~$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$~~
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	~~Q_{qqu}~~	~~$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$~~
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	~~$Q_{qqq}^{(1)}$~~	~~$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$~~
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	~~$Q_{qqq}^{(3)}$~~	~~$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$~~
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$	~~Q_{duu}~~	~~$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$~~

Some symmetries imposed to control parameter space

- CP, B and flavor conservation
- Top-specific flavour structure of 2 & 4 fermion operators

Flavor symmetry

Approximate flavor symmetry in the SM

- SM: broken by Yukawa interactions
- SMEFT: broken by $\psi^2 X\varphi, \psi^2\varphi^3, (\bar{L}R)(\bar{L}R), (\bar{L}R)(\bar{R}L)$ & $\mathcal{O}_{\varphi ud}$
- + any off-diagonal or non-universal entries of other 2F operators

SMEFTatNLO: minimal extension to single out top quark

universal $U(3)_L \times U(3)_e \times U(3)_Q \times U(3)_u \times U(3)_d$

top $U(3)_L \times U(3)_e \times U(2)_Q \times U(2)_u \times U(3)_d$

cf. Minimal flavor violation

[Buras et al.; PLB 500 (2001) 161]
[D'Ambrosio et al.; NPB 645 (2002) 155]

Yukawa	$\psi^2 H^3 : (\varphi^\dagger\varphi)^2(\bar{Q}\, t\, \tilde{\varphi})$
Dipoles	$\psi^2 XH : (\bar{Q}\,\sigma^{\mu\nu}\, t\, \tilde{\varphi})B_{\mu\nu}\ [W^I_{\mu\nu}, G^a_{\mu\nu}]$
3rd gen. currents	$\psi^2 H^2 D : (\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi)(\bar{Q}\,\gamma^\mu\, Q)\ [(\bar{Q}\,\gamma^\mu\tau^I\, Q), (\bar{t}\,\gamma^\mu\, t), \ldots]$
3rd gen. 4F	$\psi^4 : (\bar{Q}\,\gamma^\mu\, Q)(\bar{q}\,\gamma_\mu\, q), (\bar{Q}\,\gamma^\mu\, Q)(\bar{Q}\,\gamma_\mu\, Q), \ldots$

See `dim6top`

[Aguilar-Saavedra et al.; arXiv:1802.07237]

$pp \to Zh$ in SMEFT@NLO

Auto-download SMEFT@NLO

```
MG5_aMC> import model SMEFTatNLO
MG5_aMC> convert model …
MG5_aMC> quit()
```

- `python3`: copy `convert model` command
- Copy tutorial restriction card to `models/SMEFTatNLO`

```
> cp restrict_cpu_cpBB.dat /home/software/mg5amcnlo/models/SMEFTatNLO
```

```
MG5_aMC> import model SMEFTatNLO-cpu_cpBB
```

Parameter naming conventions `SMEFTsim` ⇔ `SMEFTatNLO`

- `cHu` ⇔ `cpu` & `cHB` ⇔ `cpBB` (p≡φ)

Generate process

```
MG5_aMC> generate p p > h e+ e- QCD=0 QED=3 NP=2 [QCD]
```

- Important: specify **all** coupling orders to be safe (& check diagrams!)
- Important: `NP` definition is different from `SMEFTsim` (`NP=2` is dim-6)
- Amplitude squared order not available ✘ `MG5_aMC> generate … [QCD] NP^2==2`

Diagrams

Virtual corrections

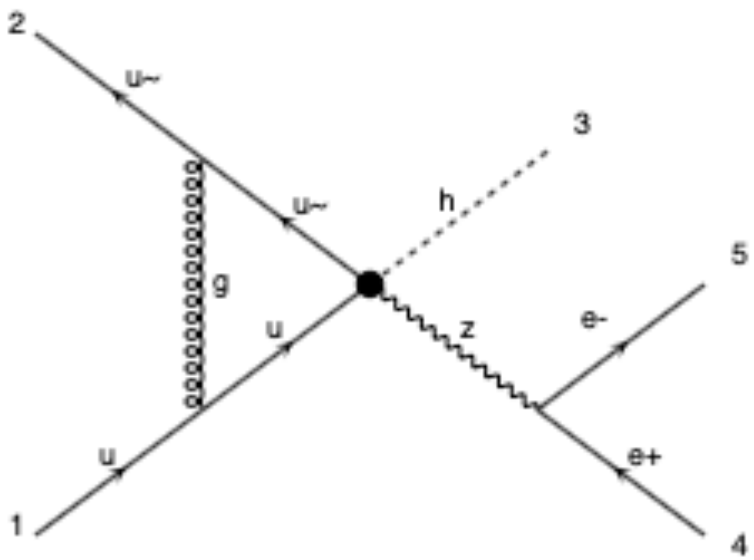


diagram 3 NP=2, QCD=2, QED=3

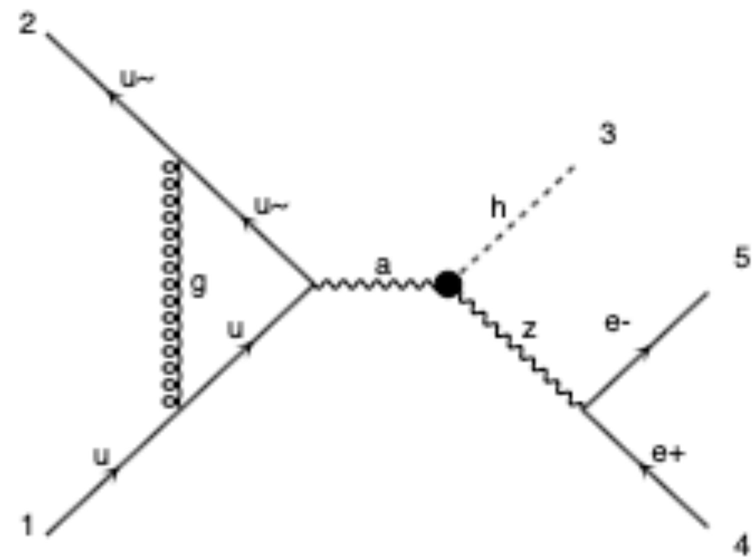
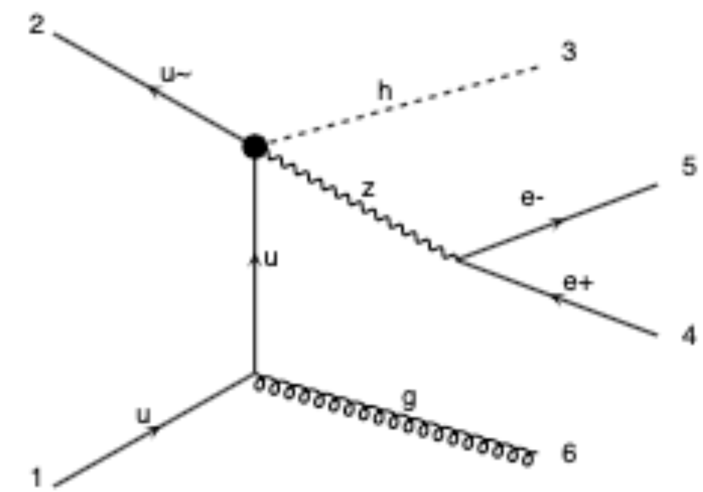


diagram 4 NP=2, QCD=2, QED=3

Real emissions



real diagram 3 NP=2, QCD=1, QED=3

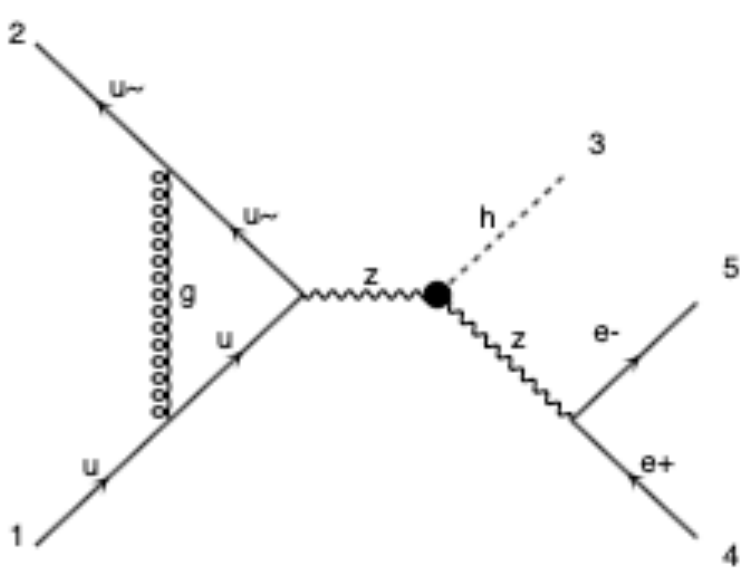


diagram 5 NP=2, QCD=2, QED=3

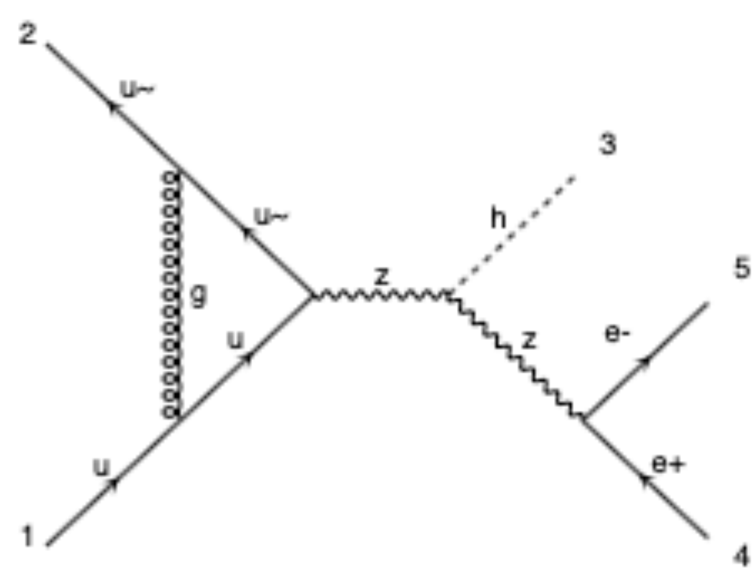
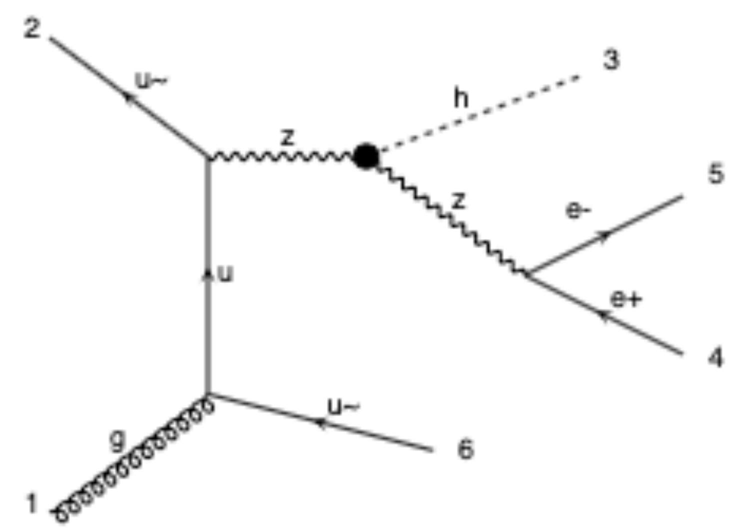


diagram 6 NP=0, QCD=2, QED=3



real diagram 12 NP=2, QCD=1, QED=3

$pp \to Zh$ in SMEFT@NLO

Sanity-check: validate `SMEFTsim` vs. `SMEFTatNLO`!

- Should get the same LO cross-sections for SM & SMEFT coefficients

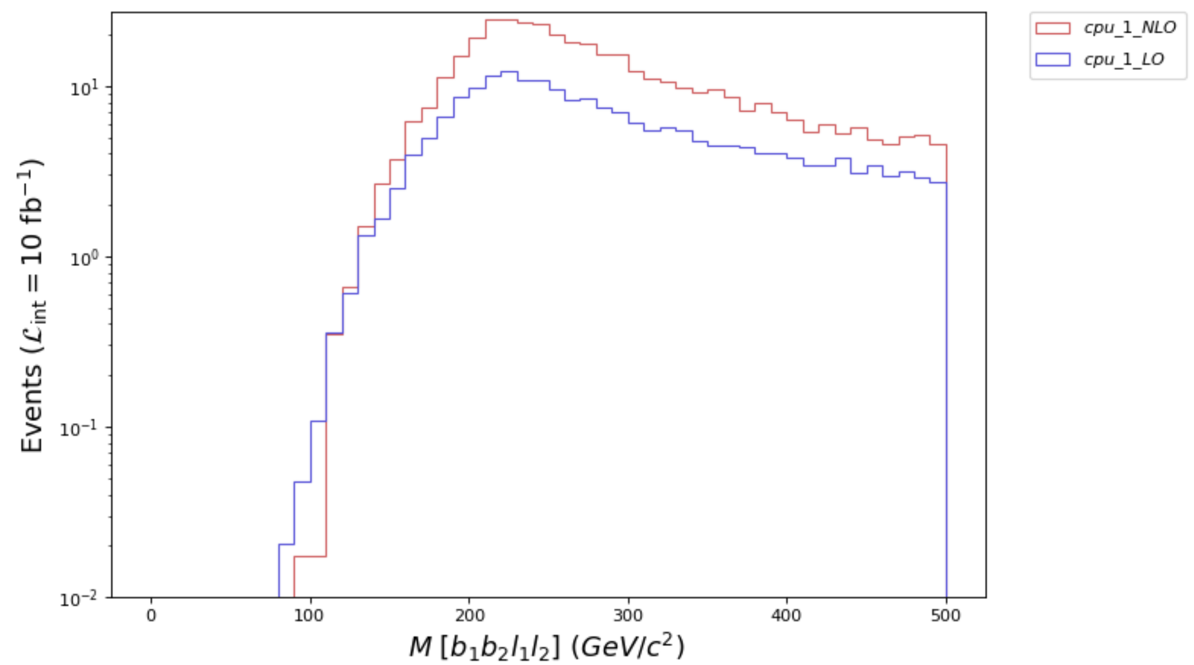
NLO predictions for SM+ $C_{HB} = 1$ & $C_{Hu} = 1$ separately

- `!Warning!` **Do not** set c's to 0 in param_card, use `1e-5` (else crash)
- Compare LO & NLO at differential-level
- Obtain K-factors (NLO/LO) for STXS bins
- Extract linear (sq) dependence:

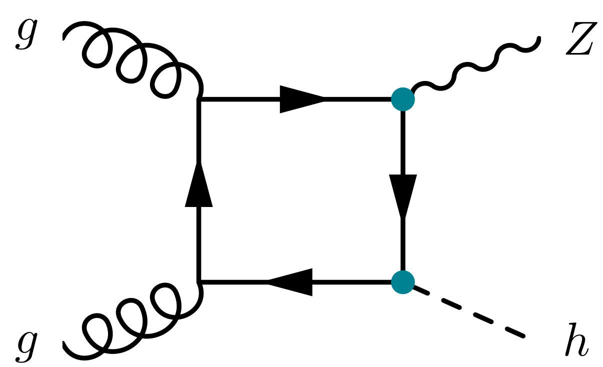
$$\sigma(c) = \sigma_{\rm SM} + c\sigma_{\rm int.} + c^2\sigma_{\rm sq.}$$

$$\sigma_{\rm int.} = \frac{1}{2}\Big(\sigma(c=+1) - \sigma(c=-1)\Big)$$

$$\sigma_{\rm sq.} = \frac{1}{2}\Big(\sigma(c=+1) + \sigma(c=-1)\Big) - \sigma_{\rm SM}$$



$qq \to Zh$ in SMEFT@NLO



Loop-induced process

- No born-level diagrams in the SM (SMEFT)
- $\mathcal{O}(\alpha_S^2)$: Formally NNLO but significant due to gluon PDFs!
- Can be sensitive to modified top quark interactions
- Today: $\mathcal{O}_{Ht} \equiv [\mathcal{O}_{Hu}]_{33} = i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{t}_R\gamma^\mu t_R)$ (model parameter: `cpt`)

```
> cp restrict_cpt.dat /home/software/mg5amcnlo/models/SMEFTatNLO
```

```
MG5_aMC> import model SMEFTatNLO-cpt
MG5_aMC> generate g g > h e+ e- QCD=0 QED=3 NP=2 [QCD]
```

Determine importance of $gg \to Zh$ w.r.t $pp \to Zh$ in SM

- Extract linear & quadratic dependence on cpt
- `!WARNING!`: Can take a long time (parton-level & ~1k events only!)
- Offline: generate showered events & compare distributions to $pp \to Zh$