Higgs Characterisation (HC) at NLO in QCD: CP properties of the top-quark Yukawa interaction

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- **HC1:** “A framework for Higgs characterisation”
  Artoisenet, de Aquino, Demartin, Frederix, Frixione, Maltoni, Mandal, Mathews, Mawatari, Ravindran, Seth, Torrielli, Zaro, JHEP11(2013)043 [arXiv:1306.6464]

- **HC2:** “Higgs characterisation via VBF/VH: NLO and parton-shower effects”
  Maltoni, Mawatari, Zaro, EPJC74(2014)2710 [arXiv:1311.1829]

- **HC3:** “Higgs characterisation at NLO in QCD: CP properties of the top Yukawa”
  Demartin, Maltoni, Mawatari, Page, Zaro, EPJC74(2014)3065 [arXiv:1407.5089]

- **HC4:** Higgs production in association with a single top quark at the LHC
  Demartin, Maltoni, Mawatari, Zaro, EPJCxx(2015)xxxx [arXiv:1504.00611]

- Sec.11 (spin/CP) in YR3 of the LHC Higgs Cross Section Working Group (HXSWG)
  de Aquino, Mawatari [arXiv:1307.1347]
H-boson observation, evidence, precision, ...

- 2012 July
  - Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC
  - Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

- 2013 July
  - Evidence for the spin-0 nature of the Higgs boson using ATLAS data

- 2013 October
  - Physics Nobel Prize [F. Englert (Brussels) and P. Higgs (Edinburgh)]

- 2015 Spring
  - LHC Run-II

looking for deviations from the SM ⇔ Higgs precision
- effective field theory (EFT) approach
- theory predictions as precise as possible
Higgs Characterisation (HC) via the FeynRules and MadGraph5_aMC@NLO frameworks

- HC provides an automated NLO+PS accurate tool and predictions to accomplish the most general and accurate characterisation of Higgs interactions in the main production and decay modes at the LHC.
- The code is publicly available at the FeynRules repository:
  https://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation

- HC1: “A framework for Higgs characterisation” JHEP11(2013)043 [arXiv:1306.6464]
  Artoisenet, de Aquino, Demartin, Frederix, Frixione, Maltoni, Mandal, Mathews, Mawatari, Ravindran, Seth, Torrielli, Zaro
  ➡ HC framework based on the effective field theory (EFT) approach

- HC2: “Higgs characterisation via VBF/VH: NLO and parton-shower effects” EPJC74(2014)2710 [arXiv:1311.1829]
  Maltoni, Mawatari, Zaro
  ➡ VBF and VH @ automated NLO+PS

- HC3: “Higgs characterisation at NLO in QCD: CP properties of the top Yukawa” EPJC74(2014)3065 [arXiv:1407.5089]
  Demartin, Maltoni, Mawatari, Page, Zaro
  ➡ GF (H+jets) and ttH @ automated NLO+PS

- HC4: “Higgs production in association with a single top quark at the LHC” EPJCxx(2015)xxxx [arXiv:1504.00611]
  Demartin, Maltoni, Mawatari, Zaro
  ➡ tH @ automated NLO+PS
FeynRules in a nutshell

Alloul, Christensen, Degrande, Duhr, Fuks [arXiv:1310.1921]
FeynRules: http://feynrules.irmp.ucl.ac.be/

• a Mathematica package that allows to derive Feynman rules from a Lagrangian.

• allows to export the Feynman rules to various matrix element generators, e.g. CalcHEP, FeynArts, MadGraph, Sherpa, Whizard, ...

• The only requirements on the Lagrangian are Locality and Lorentz invariance; no limitation for the dimensionality.

• Supported filed types are spin-0, 1/2, 1, 3/2, and 2 (as well as superfields).
MadGraph5_aMC@NLO in a nutshell

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro [arXiv:1405.0301]
MG5_aMC: https://launchpad.net/mg5amcnlo

- performs automatic computations of tree-level and NLO differential cross sections
- matches LO and NLO calculations to parton showers via the MC@NLO method
- merges LO (MLM) and NLO (FxFx) samples that differ in parton multiplicities.
Higgs Characterisation (HC) model

- We implemented an effective Lagrangian featuring bosons $X(J^P=0^+,0^-,1^+,1^-,2^+)$
  in FeynRules.

- Any-process, any-decay, any-observable (thanks to event generators, e.g. MadGraph5_aMC@NLO)

- Equally useful for theorists (it can be systematically improved, changed easily) and experimentalists (event generation easily).

- Adaptable to the present/future analyses and accuracy targets.

- The code is publicly available at the FeynRules repository: https://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation

The parametrization is based on the recent work: [Englert, Goncalves-Netto, KM, Plehn, JHEP(2013)].
Tools for Higgs Physics

Cross Section

**ggF**
- **HIGLU** (NNLO QCD+NLO EW)
- **iHixe** (NNLO QCD+NLO EW)
- **FehiPro** (NNLO QCD+NLO EW)
- **HNNLO, HRes** (NNLO+NNLL QCD)
- **SusHi** (NNLO QCD)
- **RGenHiggs** (NNLO+NNLL QCD)
- **gghiggs** (approx. NNNLO QCD)

**VBF**
- **VV2H** (NLO QCD)
- **VBFLNLO** (NLO QCD)
- **HAWK** (NLO QCD+EW)
- **VBF@NNLO** (NNLO QCD)

**WH/ZH**
- **V2HV** (NLO QCD)
- **HAWK** (NLO QCD+EW)
- **VH@NNLO** (NNLO)

**ttH**
- **HQQ** (LO QCD)

**bbH**
- **bbh@NNLO** (NNLO QCD)

**HH**
- **HPAIR** (NLO QCD)

*PDF:* **MSTW, CTEQ, NNPDF,** etc.
- **LHAPDF, HOPPET, APFEL**

**Jet-veto**
- **JetVHeto** (NNLO+NNLL)*

**Higgs p_T**
- **HqTHres**
- **ResBos** (NNLO+NNLL)

**Higgs Decay**
- **HDECAVY** (NLO++)
- **Prophecy4f** (NLO)

**Higgs Properties**
- **MELA/1HU, MEKD**
- **MG5_aMC@NLO (HC)**

**MSSM/2HDM**
- **FeynHiggs, CPSuperH**
- **SusHi+2HDMC**
- **HIGLU+HDECAVY**

* NLO+NNLL in differential

Compiled by R. Tanaka, Jan. 2014

May 4, 2015 Pheno2015@Pittsburg
Effective Lagrangian -- spin0

\[ \mathcal{L}^0_0 = - \sum_{f=t, h, \tau} \bar{\psi}_f \left( c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aeff} g_{Aeff} \gamma_5 \right) \psi_f X_0 \]

\[ \mathcal{L}^V_0 = \left\{ c_\alpha \kappa_{SM} \left[ \frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} \right] W^+ W^- \right\} \]

\[ - \frac{1}{4} \left[ c_\alpha \kappa_{H,\gamma\gamma} g_{H,\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A,\gamma\gamma} g_{A,\gamma\gamma} A_{\mu\nu} \tilde{A}^{\mu\nu} \right] \]

\[ - \frac{1}{2} \left[ c_\alpha \kappa_{H,\zeta\zeta} g_{H,\zeta\zeta} Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A,\zeta\zeta} g_{A,\zeta\zeta} Z_{\mu\nu} \tilde{A}^{\mu\nu} \right] \]

\[ - \frac{1}{4} \left[ c_\alpha \kappa_{H,gg} g_{H,gg} G^{\mu\nu} G^{\mu\nu} + s_\alpha \kappa_{A,gg} g_{A,gg} G^{\mu\nu} \tilde{G}^{\mu\nu} \right] \]

\[ - \frac{1}{4} \left[ c_\alpha \kappa_{H,\zeta\zeta} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{A,\zeta\zeta} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] \]

\[ - \frac{1}{2} \left[ c_\alpha \kappa_{H,WW} W_+ W_- + s_\alpha \kappa_{A,WW} W_+ \tilde{W}^+ \right] \]

\[ - \frac{1}{\Lambda} \left[ c_\alpha \kappa_{H,0} A_\nu \partial_\mu A^{\mu\nu} + \kappa_{H,0} \right] Z_\nu \partial_\mu Z^{\mu\nu} \]

\[ + \left( \kappa_{H,0} W_\nu \partial_\mu W^{\nu-\mu} + h.c. \right) \}

\[ X_0 \]

| Parameter | Description |
|-----------|-------------|
| \Lambda \ [\text{GeV}] | cutoff scale |
| \kappa_\alpha (\equiv \cos \alpha) | mixing between \(0^+\) and \(0^-\) |
| \kappa_i | dimensionless coupling parameter |

param_card.dat

May 4, 2015 Pheno2015@Pittsburg
Effective Lagrangian -- spin0

\[ \mathcal{L}_0^f = -\sum_{f=e,t,h,\tau} \bar{\psi}_f \left( c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{A_{ff}} g_{A_{ff}} \gamma_5 \right) \psi_f X_0 \]

\[ \mathcal{L}_0^Y = \left\{ \begin{array}{l}
\frac{1}{2} g_{ZZ} Z_\mu Z^\mu + g_{WW} W^+_\mu W^-_\mu \\
-\frac{1}{4} \left[ c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A_{\gamma\gamma}} g_{A_{\gamma\gamma}} A_{\mu\nu} A^{\mu\nu} \right] \\
-\frac{1}{2} \left[ c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma} Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma} Z_{\mu\nu} Z^{\mu\nu} \right] \\
-\frac{1}{4} \left[ c_\alpha \kappa_{Hgg} g_{Hgg} G^{a,\mu\nu} A_{\mu\nu} + s_\alpha \kappa_{A_{gg}} g_{A_{gg}} G^{a,\mu\nu} G^{a,\mu\nu} \right] \\
-\frac{1}{4} \Lambda \left[ c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] \\
-\frac{1}{2} \Lambda \left[ c_\alpha \kappa_{HHW} W^{+}_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW} W^{+}_{\mu\nu} \tilde{W}^{-\mu\nu} \right] \\
-\frac{1}{\Lambda} c_\alpha \left[ \kappa_{H\theta\gamma} A_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\theta\gamma} Z_\nu \partial_\mu Z^{\mu\nu} \right] \\
+ \left( \kappa_{H\theta\gamma} W^+_\nu \partial_\mu W^{-\mu\nu} + h.c. \right) \right\} X_0 \]

Dimensionful couplings \( g \) are set as internal parameters so as to reproduce a SM Higgs for \( \kappa=1 \).
3-min MadGraph5_aMC@NLO tutorial (ttH)

FeynRules: http://feynrules.irmp.ucl.ac.be/
MG5_aMC: https://launchpad.net/mg5amcnlo

```bash
./bin/mg5_aMC
>import model HC_NLO_X0
>generate p p > x0 t t~ [QCD]
>output pheno2015
>launch
```

- Start the MG5_aMC shell
- Import the model
- Generate the process
- Write the code (including html)
- Generate the LO/NLO events

/Users/mawatari/work/tools/madgraph5/pheno2015/index.html

### SubProcesses and Feynman diagrams

| Directory | Type | # Diagrams | # Subprocesses | FEYNMAN DIAGRAMS | SUBPROCESS |
|-----------|------|------------|----------------|------------------|------------|
| P0_gg_x0ttx | born | 8          | 1              | postscript      | g g > x0 t t~ XGLU=1 WEIGHTED=4 QNP=1 [ QCD ] WEIGHTED=1 |
|           | virt | 184        | 1              | postscript      | g g > x0 t t~ WEIGHTED=4 QNP=0 QED=1 QCD=2 [ QCD ] |
|           | real | 50         | 1              | postscript      | g g > x0 t t~ g XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] |
|           | real | 12         | 4              | postscript      | d~ g > x0 t t~ d~ XGLU=1 WEIGHTED=5 QNP=1 [ QCD ], u~ g > x0 t t~ u~ XGLU=1 WEIGHTED=5 QNP=1 [ QCD ], s~ g > x0 t t~ s~ XGLU=1 WEIGHTED=5 QNP=1 [ QCD ], c~ g > x0 t t~ c~ XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] |
born (ttH)
## SubProcesses and Feynman diagrams

| Directory  | Type  | # Diagrams | # Subprocesses | FEYNMAN DIAGRAMS                                                                 | SUBPROCESS                                      |
|-----------|-------|------------|----------------|---------------------------------------------------------------------------------|-------------------------------------------------|
| P0_gg_x0ttx | born  | 8          | 1              | postscript                                                                      | g g > x0 t t~ XGLU=1 WEIGHTED=4 QNP=1 [ QCD ] WEIGHTED=1 |
| virt      |       | 184        | 1              | postscript                                                                      | g g > x0 t t~ WEIGHTED=4 QNP=0 QED=1 QCD=2 [ QCD ] |
| real      |       | 50         | 1              | postscript                                                                      | g g > x0 t t~ g XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] |
| real      |       | 12         | 4              | postscript                                                                      | d~ d g > x0 t t~ d XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] , u~ u g > x0 t t~ u~ XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] , s~ s g > x0 t t~ s~ XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] , c~ c g > x0 t t~ c~ XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] |
| real      |       | 12         | 4              | postscript                                                                      | g d~ g > x0 t t~ d XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] , g u~ g > x0 t t~ u~ XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] , g s~ g > x0 t t~ s~ XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] , g c~ g > x0 t t~ c~ XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] |
| real      |       | 12         | 4              | postscript                                                                      | g d~ g > x0 t t~ d XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] , g u~ g > x0 t t~ u~ XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] , g s~ g > x0 t t~ s~ XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] , g c~ g > x0 t t~ c~ XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] |
| real      |       | 12         | 4              | postscript                                                                      | g d~ g > x0 t t~ d XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] , g u~ g > x0 t t~ u~ XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] , g s~ g > x0 t t~ s~ XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] , g c~ g > x0 t t~ c~ XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] |
| P0_uux_x0ttx | born  | 2          | 4              | postscript                                                                      | u u~ u > x0 t t~ XGLU=1 WEIGHTED=4 QNP=1 [ QCD ] , c c~ c > x0 t t~ XGLU=1 WEIGHTED=4 QNP=1 [ QCD ] , d d~ d > x0 t t~ XGLU=1 WEIGHTED=4 QNP=1 [ QCD ] , s s~ s > x0 t t~ XGLU=1 WEIGHTED=4 QNP=1 [ QCD ] |
| virt      |       | 41         | 4              | postscript                                                                      | u u~ u > x0 t t~ WEIGHTED=4 QNP=0 QED=1 QCD=2 [ QCD ] , c c~ c > x0 t t~ WEIGHTED=4 QNP=0 QED=1 QCD=2 [ QCD ] , d d~ d > x0 t t~ WEIGHTED=4 QNP=0 QED=1 QCD=2 [ QCD ] , s s~ s > x0 t t~ WEIGHTED=4 QNP=0 QED=1 QCD=2 [ QCD ] |
| real      |       | 12         | 4              | postscript                                                                      | u u~ u > x0 t t~ g XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] , c c~ c > x0 t t~ g XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] , d d~ d > x0 t t~ g XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] , s s~ s > x0 t t~ g XGLU=1 WEIGHTED=5 QNP=1 [ QCD ] |
virtual (ttH)
real (ttH)
3-min MadGraph5_aMC@NLO tutorial (ttH)

FeynRules: http://feynrules.irmp.ucl.ac.be/
MG5_aMC: https://launchpad.net/mg5amcnlo

./bin/mg5_aMC
>import model HC_NLO_X0
>generate p p > x0 t t~ [QCD]
>output pheno2015
>launch

Start the MG5_aMC shell
Import the model
Generate the process
Write the code (including html)
Generate the LO/NLO events

The following switches determine which operations are executed:
1. Perturbative order of the calculation:
2. Fixed order (no event generation and no MC@NLO matching):
3. Shower the generated events:
4. Decay particles with the MadSpin module:
   Either type the switch number (1 to 4) to change its default setting,
   or set any switch explicitly (e.g. type 'order=NLO' at the prompt)
   Type '0', 'auto', 'done' or just press enter when you are done.
   [0, 1, 2, 3, 4, auto, done, order=LO, order=NLO, ... ]

MadSpin: Artoisenet, Frederix, Mattelaer, Rietkert [arxiv:1212.3460]
- allows one to decay narrow resonances in Les Houches Monte Carlo events.
- preserves both spin correlation and finite width effects.
3-min MadGraph5_aMC@NLO tutorial (ttH)

Do you want to edit a card (press enter to bypass editing)?
1 / param : param_card.dat
2 / run : run_card.dat
3 / madspin : madspin_card.dat
4 / shower : shower_card.dat
[0, done, 1, param, 2, run, 3, madspin, 4, enter path, ... ]

param_card.dat

run_card.dat
The total rate and the correlations between top and antitop decay products can be sensitive to the CP nature of the Higgs boson.

NLO corrections cannot be described by an overall $K$ factor and the constant theoretical uncertainties.

HC3: Demartin, Maltoni, KM, Page, Zaro [arXiv:1407.5089]
Higgs characterisation in $tH$

HC4: Demartin, Maltoni, KM, Zaro [arXiv:1504.00611]

```
./bin/mg5_aMC
>import model HC_NLO_X0
>define p = p b b~
>define j = p
>generate p p > x0 t j $$ w+ w- [QCD]
>output pheno2015
>launch

| scheme | $\sigma_{LO}$ [fb] | $\sigma_{NLO}$ [fb] | $K$ |
|--------|---------------------|---------------------|-----|
| 4F ($\mu_0^a$) | 63.46(8) +27.2%\,-19.7% | 69.43(7) +4.0%\,-5.8% | 1.09 |
| 5F ($\mu_0^a$) | 60.66(6) +5.6%\,-10.0% | 73.45(8) +7.0%\,-2.3% | 1.21 |
| 4F ($\mu_0^d$) | 64.31(8) +27.6%\,-19.5% | 71.29(10) +3.8%\,-7.1% | 1.11 |
| 5F ($\mu_0^d$) | 58.83(5) +7.6%\,-11.9% | 71.54(7) +7.3%\,-2.1% | 1.22 |
```
Back-up
Total cross sections (ttH)

Scale and PDF uncertainties are evaluated automatically at no extra computing cost via a reweighting technique.

\[ \frac{\sigma(0^+) > \sigma(0^-)}{\sigma(0^+)} = \frac{(\sigma(0^+)+\sigma(0^-))}{2} \]

\[ \Delta\sigma(0^-) > \Delta\sigma(0^+) \]

- Scale and PDF uncertainties are evaluated automatically at no extra computing cost via a reweighting technique. Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli [arXiv:1110.4738]

- Such information is available on an event-by-event basis and therefore uncertainty bands can be plotted for any observables of interest.
The difference is significant in the low pT region.

The high-pT tail is not sensitive to the CP mixing.

Is the boosted-Higgs analyses still sensitive to the CP mixing?
Distributions without and with a boosted Higgs (ttH)

The most CP sensitive distribution is the rapidity difference between the top and antitop, which is hardly affected by the pT(X) cut.

HC3: Demartin, Maltoni, KM, Page, Zaro [arXiv:1407.5089]
Correlations between the top-decay products (ttH) 
(in the di-leptonic channel)

- As expected from the $\Delta \eta(t)$, $\Delta \eta(l)$ and $\Delta \eta(b)$ are almost insensitive to the $p_T(X)$ cut, while the angle between the leptons (b jets) is significantly affected by the boost.
Theoretical uncertainties (ttH)

HC3: Demartin, Maltoni, KM, Page, Zaro [arXiv:1407.5089]

| scenario  | $\sigma_{LO}$ (fb)       | $\sigma_{NLO}$ (fb)       | $K$       |
|-----------|--------------------------|---------------------------|-----------|
| 0$^+$ LHC 8 TeV | 130.3(1) $^{+36.8}_{-24.6}$ $^{+5.9\%}_{-3.3\%}$ | 134.9(2) $^{+3.2}_{-8.3}$ $^{+3.0\%}_{-3.0\%}$ | 1.04      |
| 0$^-$ LHC 8 TeV | 44.49(4) $^{+42.6}_{-27.6}$ $^{+10.3\%}_{-6.0\%}$ | 47.07(6) $^{+6.5}_{-11.5}$ $^{+4.9\%}_{-4.9\%}$ | 1.06      |
| 0$^\pm$ LHC 8 TeV | 87.44(8) $^{+38.2}_{-25.4}$ $^{+6.9\%}_{-4.1\%}$ | 90.93(12) $^{+3.9}_{-9.1}$ $^{+3.4\%}_{-3.4\%}$ | 1.04      |
| 0$^+$ LHC 13 TeV | 468.6(4) $^{+32.8}_{-22.8}$ $^{+4.5\%}_{-3.7\%}$ | 525.1(7) $^{+5.7}_{-8.7}$ $^{+2.1\%}_{-2.1\%}$ | 1.12      |
| 0$^-$ LHC 13 TeV | 196.8(2) $^{+37.1}_{-25.1}$ $^{+7.5\%}_{-5.0\%}$ | 224.3(3) $^{+6.8}_{-10.5}$ $^{+3.2\%}_{-3.2\%}$ | 1.14      |
| 0$^\pm$ LHC 13 TeV | 332.4(3) $^{+34.0}_{-23.5}$ $^{+5.4\%}_{-3.4\%}$ | 374.1(5) $^{+6.0}_{-9.3}$ $^{+2.5\%}_{-2.5\%}$ | 1.13      |

The NLO corrections
- considerably reduce the theoretical uncertainties.
- cannot be described by an overall $K$ factor and the constant theoretical uncertainties.
The mjj distributions are all very similar (except the scenario with the derivative operator).

The QCD corrections tend to make the tagging jets softer.
The unitarity violating behavior of the HD interactions, especially HDder, clearly manifests itself.

HC2: Maltoni, KM, Zaro [arXiv:1311.1829]
The $mjj$ cut effectively suppresses the central jet activity, especially for SM.

The difference among the scenarios becomes more pronounced.

NLO corrections cannot be described by an overall $K$ factor, and also depends on the applied cuts.
**Higgs + 2 jets**

**HC2: Maltoni, KM, Zaro [arXiv:1311.1829]**

```
./bin/mg5_aMC
>import model HC_NLO_X0
>generate p p > x0 j j $$ w+ w- z QCD=0 [QCD]
>output
>launch
```

**HC3: Demartin, Maltoni, KM, Page, Zaro [arXiv:1407.5089]**

```
./bin/mg5_aMC
>import model HC_NLO_X0-heft
>generate p p > x0 j j / t [QCD]
>output
>launch
```
Di-jet correlations are still sensitive probes of the CP mixing of the Higgs boson even after PS.

HC3: Demartin, Maltoni, KM, Page, Zaro [arXiv:1407.5089]
## Vector-boson associated production (VH)

| Scenario          | HC Parameter Choice                                      |
|-------------------|----------------------------------------------------------|
| $0^+$ (SM)        | $\kappa^{SM} = 1 \ (c_{\alpha} = 1)$                   |
| $0^+$ (HD)        | $\kappa^{HZZ,HWW} = 1 \ (c_{\alpha} = 1)$               |
| $0^+$ (HDder)     | $\kappa^{HZZ,HWW} = 1 \ (c_{\alpha} = 1)$               |
| $0^+$ (SM+HD)     | $\kappa^{SM,HZZ,HWW} = 1 \ (c_{\alpha} = 1, \Lambda = \nu)$ |
| $0^-$ (HD)        | $\kappa^{AZZ,AWW} = 1 \ (c_{\alpha} = 0)$               |
| $0^\pm$ (HD)      | $\kappa^{HZZ,AZZ,HWW,AWW} = 1 \ (c_{\alpha} = 1/\sqrt{2})$|

| Scenario          | $\sigma_{LO}$ (fb)     | $\sigma_{NLO}$ (fb)     | $K$ |
|-------------------|-------------------------|-------------------------|-----|
| $0^+$ (SM)        | 10.13(1) $^{+0.0\%}_{-0.5\%}$ | 13.24(1) $^{+2.2\%}_{-1.7\%}$ | 1.31 |
| $0^+$ (HD)        | 2.638(2) $^{+1.4\%}_{-1.7\%}$  | 3.461(3) $^{+1.9\%}_{-1.3\%}$  | 1.31 |
| $0^+$ (HDder)     | 48.61(4) $^{+4.2\%}_{-3.9\%}$  | 63.59(5) $^{+2.1\%}_{-1.9\%}$  | 1.31 |
| $0^+$ (SM+HD)     | 19.95(1) $^{+3.1\%}_{-1.8\%}$  | 26.24(2) $^{+1.8\%}_{-1.6\%}$  | 1.32 |
| $0^-$ (HD)        | 1.480(1) $^{+2.6\%}_{-2.7\%}$  | 1.952(1) $^{+1.7\%}_{-1.5\%}$  | 1.32 |
| $0^\pm$ (HD)      | 2.061(1) $^{+1.9\%}_{-2.0\%}$  | 2.705(2) $^{+1.8\%}_{-1.3\%}$  | 1.31 |

- Scale and PDF uncertainties are evaluated automatically at no extra computing cost via a reweighting technique.
- Such information is available on an event-by-event basis and therefore uncertainty bands can be plotted for any observables of interest.
Higgs decay to 4 leptons

\texttt{./bin/mg5\_aMC}

\texttt{import model HC}

\texttt{generate p p > x0, x0 > mu- mu+ e- e+}

\texttt{launch}

HC1: Artoisenet et al. [arXiv:1306.6464]