Tutorial on HiggsPO tool[1]

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Abstract

This note explains how to use HiggsPO tool to generate signal events for Higgs boson production and decay analyses at the LHC. Two examples are provided; (1) $h \to 4\ell$ in gluon fusion Higgs production and (2) $h \to \gamma\gamma$ in VBF Higgs production.

Contents

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1 General remarks

Pseudo-observables (PO) proposed in Ref. [2] (for Higgs decays) and Ref. [3] (for electroweak Higgs production) are a framework for parameterizing possible deviations from the SM in great generality. A set of PO is defined at the amplitude level as residues of physical poles in the momentum expansion of the amplitude. On one hand, they can be computed in a specific Lagrangian realization and at the specific order in perturbation theory. On the other hand, PO are directly linked to the S-matrix element, and therefore unambiguously related to the physical observables. Furthermore, in order to use amplitude decomposition for precision studies, it is important to account for the long-distance contributions due to the leading QED and QCD radiative corrections. These represent a universal correction factor that can be implemented, irrespective of the specific short-distance structure of the amplitude. It has been shown that inclusion of such correction in $h \to 2e2\mu$ recovers the complete next-to-leading-order Standard Model predictions within 1% accuracy [4].

In order to apply this framework to an experimental analysis it is often convenient to have a Monte Carlo tool capable of generating signal events for specific values of the PO. We build a FeynRules [5] model, *HiggsPO* [1], with the only aim of describing the short-distance contributions to Higgs decay amplitudes in terms of PO. The model is exported in UFO [6] format, which is to be used within the MadGraph5_aMC@NLO [7] or Sherpa+OpenLoops [8, 9] frameworks. We stress that our FeynRules implementation consists of a set of effective interactions that at tree level generate exactly the scattering amplitude of interest and is supposed to be used for this purpose only: not to be used as a Lagrangian for arbitrary process and beyond tree level.

In principle, our tool can be used standalone or together with other tools. For example, gluon fusion Higgs production can be simulated with some other dedicated montecarlo, while simulating decays within *HiggsPO* and then the partonic events can be passed to a general purpose event generators for subsequent showering and hadronization.

The *HiggsPO* tool, together with other supporting documentation, can be found at: http://www.physik.uzh.ch/data/HiggsPO.

For the purpose of this tutorial, the user is advised to download: **HPOprodMFV_UFO** and copy it into /models/ subfolder of MadGraph5_aMC@NLO installation. The exercises are tested with version 2.3.3 of MadGraph5_aMC@NLO. We also use extra packages: Pythia, Delphes and MadAnalysis, that can be installed through mg5_aMC. For details see [7].

2 ggF with $h \to 4\ell$

In this exercise we use Higgs PO framework to study gluon fusion Higgs production (ggF) followed by $h \to 4\ell$ decay where $\ell = e, \mu$. We first discuss separately production and decay simulations with *HiggsPO* tool and finally perform the combined analysis in the last subsection.

2.1 ggF

Gluon fusion production is parameterised with a single PO only, which allows for modification in the total rate. This variable is denoted with `eggSM` and can freely be modified in the `param_card.dat`. To simulate ggF production at LO, open a terminal and start mg5_aMC, then write into the command line:

```
> import model HPOprodMFV_UFO
> generate p p > h
> output ppH
```

This creates a folder `/ppH/` in the local directory. To check the details on the process generation (diagrams, etc.) see `/ppH/index.html`. The `param_card.dat` can be found in `/ppH/Cards/` subfolder. It contains all PO parameters as implemented in *HiggsPO*, grouped into several blocks: `HPO2F`, `HPO4F` and `HPOQUARK`. Standard Model parameters are given in `HPOSM` and `SMPARAM` blocks. Effective W and Z boson couplings PO are given in `WZPOLE` block. The `param_card.dat` also contains information about the mass and total decay width of all the particles. As a warm-up exercise, do the following:
(1) Check the default input in the `param_card.dat`, for example, Higgs mass and width, `eggSM`, etc.
(2) Run the simulation at parton and hadron level (create `pythia_card.dat` from the default one) for 8 and 13 TeV c.m. energies, (set the collider energy in `run_card.dat`, and remove all kinematical cuts). To produce events, write into the MadGraph command line:

```
> launch ppH
```

The events (`.lhe` file for parton, and `.hep` for hadron level) are stored in `/ppH/Events/run_x/` subfolder. In particular, `run_x_tag_1_banner.txt` file contains all the information about the run. The results can also be viewed at `/ppH/crossx.html`.
(3) Compare the obtained cross section with the best inclusive predictions from LHC Higgs cross section working group, $\sigma_{\rm ggF}^{\rm SM} = 19.3$ (43.9) pb at 8 (13) TeV. Notice the large higher-order QCD correction K_F (by default `eggSM` is matched to the leading one-loop top quark contribution in the SM).

In order to have a reliable prediction of ggF production kinematics, one needs to take into account higher order QCD corrections. Here we employ ME+PS jet merging which provides a good description of the Higgs p_T distribution (see for example Ref. [11]). We write in the MadGraph command line:

```
> import model HPOprodMFV_UFO
> generate p p > h
> add process p p > h j
> output ppHj
```

For simplicity (and computational power), we stop at one extra jet. In principle, one could generate matrix elements for hard scatterings: $pp \to h$ + 0,1 and 2 extra partons. We then proceed by switching on MLM-k_T scheme for merging in the `run_card.dat`:

```
1 = ickkw !  0 no matching, 1 MLM, 2 CKKW matching
```

and choose jet measure cut:

```
25 = xqcut !  minimum kt jet measure between partons
```

Finally, create `pythia_card.dat` from the default card and add:

```
!...Cutoff in jet measure for matching
QCUT = 40
```

After this is done, remove all kinematical cuts in `run_card.dat` and run the simulation for 13 TeV.

(1) Compare the matched cross section to the one obtained before.

(2) In order to validate the merging procedure, check the differential jet rate distribution plot produced by MadAnalysis.

(3) Compare the leading jet p_T distribution with the one obtained before.

2.2 $h \to 4\ell$

The "golden channel" decay mode ($h \to 4\ell$) is described by 11 PO in full generality [2]. These are: κ_{ZZ} (`kZZ`), ϵ_{Ze_L} (`eZeL`), ϵ_{Ze_R} (`eZeR`), $\epsilon_{Z\mu_L}$ (`eZmuL`), $\epsilon_{Z\mu_R}$ (`eZmuR`), ϵ_{ZZ} (`eZZ`), $\kappa_{Z\gamma}$ (`kZA`), $\kappa_{\gamma\gamma}$ (`kAA`), $\epsilon_{ZZ}^{\rm CP}$ (`eZZCP`), $\lambda_{Z\gamma}^{\rm CP}$ (`lZACP`) and $\lambda_{\gamma\gamma}^{\rm CP}$ (`lAACP`), where the corresponding `param_card.dat` label is given in the brackets. These are shown in `HPO4F` block. The number of PO reduces under symmetry and/or dynamical assumptions [2].

The matrix element squared and summed over the final lepton spins,

$$|\hat{\mathcal{A}}_{4\ell}|^2 = \sum_{\rm spins} \left| \mathcal{A}\left[h \to \ell(p_1)\bar{\ell}(p_2)\ell(p_3)\bar{\ell}(p_4) \right] \right|^2 \ , \tag{1}$$

is a quadratic polinomial in $\kappa \equiv \left(\kappa_{ZZ}, \epsilon_{Ze_L}, \epsilon_{Ze_R}, \epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}, \epsilon_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}^{\rm CP}, \lambda_{Z\gamma}^{\rm CP}, \lambda_{\gamma\gamma}^{\rm CP}\right)^T$, that is,

$$|\hat{\mathcal{A}}_{4\ell}|^2 = \sum_{j\geq i} X_{ij}^{4\ell} \kappa_i \kappa_j \ . \tag{2}$$

where $X_{ij}^{4\ell}$ function depend on the kinematics of the event. This implies that eventually at the analysis level, the number of signal events in a given bin, will exhibit a **simple quadratic form** dependence on PO. This observation constitutes a tremendous simplification of the signal generation procedure with a Monte Carlo tool. In fact, to fully determine the triangle matrix $X_{ij}^{4\ell}$, one needs to run the simulation for $N(N+1)/2$ points in the parameter space of PO, where N is the total number of PO. Based on these runs, the number of signal events as a function of PO is **completely** determined over the full PO space.

To generate $h \to 4\ell$, write in the command line:

```
> import model HPOprodMFV_UFO
> generate h > l+ l- l+ l- HPO=1 YUK=0
> output Hllll
```

(1) Check the diagrams (Note that YUK=0 is needed to remove $h\bar{f}f$ contributions. All generated diagrams have correct order HPO=1. Try to identify individual diagrams with the amplitude decomposition in Ref. [2]).
(2) Set all Higgs PO to 0 in the `param_card.dat` but κ_{ZZ}. In the `plot_card.dat`, change the range for `pT` and `mij` variables from 0 to 125 with a step of 5. In the `run_card.dat`, set `nevents` to 100k. Run the simulation. Check the total decay widths for each sub-channel at `/Hllll/HTML/run_01/results.html`. These should be at the $\sim$ percent level agreement with predictions from the LHC Higgs cross section working group [12].
(3) Set $\kappa_{ZA} = 5$ in the `param_card.dat`. In the `run_card.dat`, set

```
1.0 = mmll !  min invariant mass of l+l- (same flavour) lepton pair
```

Compare dilepton invariant mass distribution plots for the two runs.

2.3 $pp \to h \to 4\ell$

In order to perform a full simulation of $pp \to h \to 4\ell$, write into the MadGraph command line:

```
> import model HPOprodMFV_UFO
> generate p p > h , h > l+ l- l+ l- HPO=1 YUK=0
> add process p p > h j , h > l+ l- l+ l- HPO=1 YUK=0
> output ppHjllll
```

It is instructive to check the generated diagrams and compare with the previous runs. For simplicity, here we study in detail $h \to 2e2\mu$ decay. Write into the MadGraph command line:

```
> import model HPOprodMFV_UFO
> generate p p > h , h > e+ e- mu+ mu- HPO=1 YUK=0
> add process p p > h j , h > e+ e- mu+ mu- HPO=1 YUK=0
> output ppHjeemumu
```

After generating the process, do the following:

- Set all Higgs PO to 0 in the `param_card.dat` but κ_{ZZ}. Modify the `run_card.dat` and `pythia_card.dat` in exactly the same way as for ggF merging procedure done above (except for `nevents` to 50k). Create `delphes_card.dat` (use the default ATLAS card). In the `plot_card.dat`, change the range for `mij` variable from 0 to 120 with a step of 6. Run the simulation: `> launch ppHjeemumu`.

- Using the decay width computed above, the total Higgs width and the best determination of the ggF cross section, determine the QCD correction factor K_F for the signal normalisation. ($K_F \sim 2.4$).

- Compare the dilepton invariant mass distributions: $m_{\mu^+\mu^-}$ and $m_{e^+e^-}$. The plots generated by MadAnalysis at parton level:
  `/ppHjeemumu/HTML/run_01/plots_parton.html`
  hadron level:
  `/ppHjeemumu/HTML/run_01/plots_pythia_tag_1.html`
  and detector level:
  `/ppHjeemumu/HTML/run_01/plots_delphes_tag_1.html`
  Notice the QED showering effects (see Fig. 1 and the discussion in the caption).

To illustrate Higgs PO usage in a realistic analysis, let us now perform a simplified fit to the dimuon invariant mass distribution ($m_{\mu^+\mu^-}$) in terms of three PO:

$$\kappa \equiv (\kappa_{ZZ}, \epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}) \ . \tag{3}$$

First, impose the following set of cuts in `run_card.dat`: charged lepton $p_T > 6$ GeV and $|\eta| < 2.7$ and minimum invariant mass of the same flavour opposite-sign lepton pair $m_{\ell\ell} > 12$ GeV. In `delphes_card.dat`, set anti-k_T jet algorithm with cone size 0.4. Also, modify electron and muon isolation parameters: `DeltaRMax` to 0.3 and `PTRatioMax` to 0.5. Now, simulate events for the three following points:

$$\kappa_1 = (1,0,0) \ ; \ \kappa_2 = (0,1,0) \ ; \ \kappa_3 = (0,0,1) \ . \tag{4}$$

To run multiple points, it is convenient to use MadEvent. Write in the terminal
`./ppHjeemumu/bin/madevent < scan_diag.mg5`
where the content of `scan_diag.mg5` file is:

```
generate_events

set hpo4f 1 1.0
set hpo4f 12 0.0
set hpo4f 15 0.0

generate_events

set hpo4f 1 0.0
set hpo4f 12 1.0
set hpo4f 15 0.0

generate_events
set hpo4f 1 0.0
```

```
set hpo4f 12 0.0
set hpo4f 15 1.0
```

Here, the command set is used to change the input values of the parameters in `HPO4F` block in `param_card.dat`. Now run the points

$$\kappa_4 = (1, 0.4, 0) \ ; \ \kappa_5 = (1, 0, 0.4) \ ; \ \kappa_6 = (0, 1, 1) \ . \tag{5}$$

These are chosen in such a way to maximize the contribution from the interference terms (i.e. $\epsilon_{Z\mu_L} = \kappa_{ZZ}\sqrt{\sigma_1/\sigma_2}$ for Run 4), thus, reducing the Monte Carlo error.

Based on these six runs, it is possible to compute the number of signal events in each bin **for arbitrary PO**. Do the following simple exercise:

- Compute the dependence of the total matched cross section on PO, using information from `/ppHjeemumu/crossx.html`

$$\frac{\sigma_{tot}}{\sigma_{tot}^{SM}} = \begin{pmatrix} \kappa_{ZZ} & \kappa_{Z\mu_L} & \kappa_{Z\mu_R} \end{pmatrix} \begin{pmatrix} 1.0 & 3.0 & -2.6 \\ 0 & 6.4 & 0.0 \\ 0 & 0 & 6.4 \end{pmatrix} \begin{pmatrix} \kappa_{ZZ} \\ \epsilon_{Z\mu_L} \\ \epsilon_{Z\mu_R} \end{pmatrix} . \tag{6}$$

- Download `2e2mu-analysis-lhco.zip` from [1]. Execute `2e2mu-analysis-lhco.nb` analysis file. It reads in `.lhco` files for each run and makes histogram in the $m_{\mu^+\mu^-}$ variable in the range $12 - 96$ GeV in step of 12 GeV. It then computes a quadratic function in PO for the number of signal events in each bin. It also performs a simplified statistical analysis and computes the projections for 300 fb^{-1}.

3 VBF with $h \to \gamma\gamma$

In order to perform a simulation of VBF with $h \to \gamma\gamma$, write into the MadGraph command line:

```
> import model HPOprodMFV_UFO
> generate p p > h j j $$ a z w+ w- HPO=1 QCD=0 YUK=0, h > a a
> output VBFtoAA
```

Here, `$$` is used to remove the s-channel contribution which is a part of VH production [3]. Check the generated diagrams at `/VBFtoAA/index.html`. Full NLO QCD corrections will be included in the next update of *HiggsPO*, meanwhile, as shown in Ref. [3], flat K_F are obtained if renormalization and factorization scales are set to $H_T/2$. This can be done in `/VBFtoAA/SubProcesses/setscales.f` by modifying `dynamical_scale_choice` routine.

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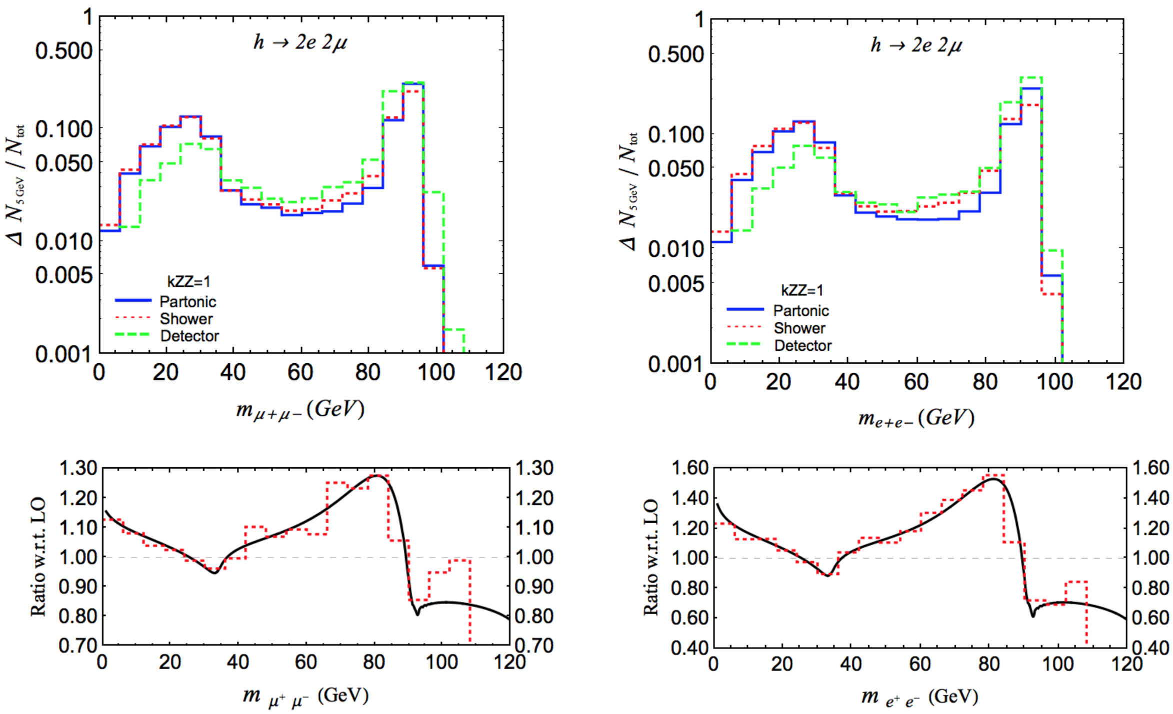

Figure 1: Normalised $h \to e^+e^-\mu^+\mu^-$ differential distributions in muon (left plot) and electron (right plot) pair invariant mass. Shown in blue is the partonic level distribution as obtained by MadEvent while shown in red-dotted is the distribution obtained after showering with Pythia 6.4. Green-dashed is the distribution after simulating detector level effects with Delphes 3.3.0 and using the default ATLAS card. Plots in the lower panel show the ratio of red-dotted over blue from the upper plots. Shown in solid-black is the theoretical prediction obtained after convolution of QED corrections using formulas from Ref. [4] and setting m_* parameter to muon and electron mass, respectively. As shown in Ref. [4], these can account for the dominate NLO electroweak corrections as obtained with Prophecy4f generator.

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