

# Manual for the JHU generator

For simulation of a single-produced resonance at hadron colliders  
(version v6.8.4, release date Jan. 07, 2016, manual date Jan. 07, 2016)

The generator from [1–3] is a model-independent generator for studying spin and parity properties of new resonances. Please cite [1–3] if using the "JHU generator". The code can be downloaded from [4]. The generator outputs LHE files which can be passed to parton shower programs for hadronization. Only relative values of cross sections are supposed to produce meaningful results, while absolute values are often subject to an arbitrary normalization.

Additionally, the package includes code for computing the matrix elements standalone which can be used in a numerical matrix element analysis. Please reference the above papers and refer to "MELA" when using the matrix element likelihood analysis technique. The latter was also introduced in Ref. [5]. The matrix element package (MELA) also depends on MCFM libraries for background parameterization which should be referenced [6] when used.

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## I. INSTALLATION

Register and download the package from [www.pha.jhu.edu/spin](http://www.pha.jhu.edu/spin) and untar the file. Go to the directory `JHUGenerator` where the code exists for generating events with the JHU Generator. In the `makefile`, you have two options for compiler, `Comp = ifort` or `Comp = gfort`. Then simply compile with:

```
$ make
```

## II. CONFIGURATION

There are two ways to configure the program, from the command line and in the file `mod_Parameters.F90`. For documentation from the command line, one can use `JHUGen help`. In addition, the command line configurables are defined in the file `main.F90`. When one change the fortran code directly, one should also recompile the code for changes to take effect. In general, command-line configuration handles general event properties while the configuration file handles all of the couplings and physics handles.

### A. Command line configuration

The list of command line configurables and the default values are (also defined in the `README`):

<b>Collider:</b>	1=LHC, 2=Tevatron, 0=e+e-
<b>Process:</b>	0=spin-0, 1=spin-1, 2=spin-2 resonance, 50=pp/ee->VH, 60=weakVBF, 61=pp->Hjj, 62=pp->Hj, 80=ttH, 90=bbH, 110=t+H t channel, 111=tbar+H t channel, 112=t+H s channel, 113=tbar+H s channel
<b>MReso:</b>	resonance mass (default=125.00), format: yyy.xx
<b>DecayMode1:</b>	decay mode for vector boson 1 (Z/W/gamma)
<b>DecayMode2:</b>	decay mode for vector boson 2 (Z/W/gamma) 0=Z->2l, 1=Z->2q, 2=Z->2tau, 3=Z->2nu, 4=W->lnu, 5=W->2q, 6=W->taunu, 7=gamma, 8=Z->2l+2tau, 9=Z->anything, 10=W->lnu+taunu, 11=W->anything
<b>PChannel:</b>	0=g+g, 1=q+qb, 2=both
<b>OffXVV:</b>	off-shell option for resonance(X),or vector bosons(VV)
<b>PDFSet:</b>	1=CTEQ6L1(2001), 2=MSTW(2008), 2xx=MSTW with eigenvector set xx=01..40, 3=NNPDF3.0LO
<b>VegasNc0:</b>	number of evaluations for integrand scan
<b>VegasNc1:</b>	number of evaluations for accept-reject sampling
<b>VegasNc2:</b>	number of events for accept-reject sampling
<b>Unweighted:</b>	0=weighted events, 1=unweighted events
<b>Interf:</b>	0=neglect interference for 4f final states, 1=include interference
<b>DataFile:</b>	LHE output file
<b>ReadLHE:</b>	LHE input file from external file (only spin-0)
<b>ConvertLHE:</b>	Convert decay of the V from VH production. Use DecayMode1 to specify the decay. (should be a Z or W mode, depending on the input file)
<b>TopDK:</b>	For ttH or t+H, 0=leave top quarks as stable, 1=decay top quarks
<b>FilterNLept:</b>	For decay mode, reject events that have less than FilterNLept leptons
<b>FilterOSPairs:</b>	For decay mode, reject events that have less than FilterOSPairs pairs of sign leptons of any flavor.
<b>FilterOSSFPairs:</b>	For decay mode, reject events that have less than FilterOSSFPairs pairs of opposite-sign-same-flavor leptons.
<b>CountTauAsAny:</b>	For FilterOSSFPairs, taus can stand in place of electrons or muons of the same charge.

**LHAPDF:** PDF set to use if interfaced with LHAPDF. See below.  
**FacScheme:** PDF factorization scale scheme  
**MuFacMultiplier:** Multiplier for the factorization scale chosen by FacScheme  
**RenScheme:** QCD renormalization scale scheme  
**MuRenMultiplier:** Multiplier for the renormalization scale chosen by RenScheme  
**WidthScheme:** Higgs width scheme: 0 for fixed width (default), 1 for running width,  
 and 2 for the CPS  
**WriteFailedEvents:** Write events that fail in the LHE file, but with a weight of 0  
 (off by default)

A few more details on some particular parameters:

- **VegasNc0,1,2:** For unweighted event generation **VegasNc0** specifies the number of evaluations for the initial integrand scan. The actual event generation is controlled by either **VegasNc1** or **VegasNc2**. **VegasNc1** specifies the number of tries in the accept/reject phase and **VegasNc2** is the number of generated events. When generating unweighted events in **ReadLHE** mode, both **VegasNc1** or **VegasNc2** can be used to specify the number of generated events. For the generation of weighted events **VegasNc1** specifies the number of evaluations for each of 5 iterations during the initial integrand scan. **VegasNc2** gives the (approximate) number of generated weighted events.
- **OffXVV:** The program does not work for  $ZZ$  or  $WW$  if you set them to be on-shell (**OffXVV**="000") and the mass of the  $X$  resonance to be below the  $m_{VV}$  threshold. In general, the more off-shell the process, or the more "1" you have, the less efficient the **VegasNc1** evaluations are. Specifically, if you are interested then, in producing a resonance with mass below threshold  $m_{VV}$  with a very narrow resonance, it is most efficient to generate with **OffXVV**="011"
- **PChannel:** This parameter is only meaningful in the spin-2 case and for the  $ttH$  and  $bbH$  production mechanisms. For spin-0, production is possible only via the  $gg$  process; for spin-1 and for the VBF and  $VH$  processes, production is only possible via the  $q\bar{q}$  process. For  $H + jj$  and  $H + j$ , all four parton channels  $gg$ ,  $q\bar{q}$ ,  $qg$ , and  $gq$  are included.
- **DecayMode1,2=7:** Valid for spin-0 and spin-2. Only **OffXVV**=000 or 100 are possible.
- In  $VH$  production and **ConvertLHE** mode, **DecayMode1** is used for the decay of the  $V$ . If it is a  $Z$  decay mode,  $ZH$  will be produced; if it is a  $W$  decay mode,  $WH$  will be produced.
- In  $ttH$  production, **DecayMode1** and **DecayMode2** are used to decay the  $W$  bosons from the top decay. Only  $W$  decay modes are allowed.
- In  $t + H$  production, **DecayMode1** is used to decay the  $W$  boson from the top decay.
- **Interf:** For final states with 4 same flavor fermions, this parameter controls whether or not to include interference effects.
- **FacScheme, MuFacMultiplier, and RenScheme, MuRenMultiplier:** There are currently 10 different schemes, which set the basis of the scale up to the scale multiplier. A positive integer uses running scales per event whereas a negative one uses a fixed scale, and **MuFacMultiplier** and **MuRenMultiplier** determine the scale multipliers for the factorization and renormalization scales, respectively:
  - $\pm 0$ :  $\mu_{F,R}$  are set to the default values of each process. The command line values of **MuFacMultiplier** and **MuRenMultiplier** are disregarded.
  - $\pm 1$ :  $\mu_{F,R} \propto \sqrt{q_H^2}$  if the scheme number is positive, or  $\mu_{F,R} \propto m_H$  if the scheme number is negative. +1 is the default value for **Process** 0, 1 and 2 with scale multiplier 0.5, and  $-1$  is the default value for **Process** 50, 60, 61 and 62 with scale multiplier 1.
  - $\pm 2$ : If the scheme number is positive,  $\mu_{F,R} \propto \sqrt{q_{JJH}^2}$ , where  $J$  refers to a particle (partons or leptons) immediately associated in the Higgs production. If the scheme number is negative and the Higgs and the associated partons originate from a common particle (e.g.  $V^*$  in  $VH$ ),  $\mu_{F,R} \propto m_{JJH}$ .
  - $\pm 3$ : If the scheme number is positive,  $\mu_{F,R} \propto \sqrt{q_{JJ}^2} + \sqrt{q_H^2}$ . If the scheme number is negative and the associated particles originate from a common particle without the Higgs (e.g.  $V$  in  $VH$ ),  $\mu_{F,R} \propto m_{JJ} + m_H$ .

- $\pm 4$ : If the scheme number is positive,  $\mu_{F,R} \propto \sqrt{q_{J_1}^2} + \sqrt{q_{J_2}^2} + \sqrt{q_H^2}$ , where  $J_{1,2}$  are the associated particles. If the scheme number is negative and the matrix element treats the associated particles as massive (e.g.  $t$  and  $\bar{t}$  in  $t\bar{t}H$ ),  $\mu_{F,R} \propto m_{J_1} + m_{J_2} + m_H$ .  $-4$  is the default value for **Process** 80 and 90 with scale multiplier 0.5.
- $\pm 5$ : If the scheme number is positive,  $\mu_{F,R} \propto \sqrt{q_{JJ}^2}$ . If the scheme number is negative and the associated particles originate from a common particle without the Higgs (e.g.  $V$  in  $VH$ ),  $\mu_{F,R} \propto m_{JJ}$ .
- $\pm 6$ : If the scheme number is positive,  $\mu_{F,R} \propto \sqrt{q_{J_1}^2} + \sqrt{q_{J_2}^2}$ , where  $J_{1,2}$  are the associated particles. If the scheme number is negative and the matrix element treats the associated particles as massive (e.g.  $t$  and  $\bar{t}$  in  $t\bar{t}H$ ),  $\mu_{F,R} \propto m_{J_1} + m_{J_2}$ .
- $\pm 7$ : If the scheme number is positive,  $\mu_{F,R} \propto \sqrt{q_{JH}^2}$ , where  $J$  is the more massive associated particle by its pole mass. If the scheme number is negative and the matrix element treats an associated particle as massive (e.g.  $t$  in  $t + H$ ),  $\mu_{F,R} \propto m_J + m_H$  for the most massive associated particle.
- $\pm 8$ : If the scheme number is positive,  $\mu_{F,R} \propto \sqrt{q_J^2} + \sqrt{q_H^2}$ , where  $J$  is the more massive associated particle. If the scheme number is negative and the matrix element treats an associated particle as massive (e.g.  $t$  in  $t + H$ ),  $\mu_{F,R} \propto m_J + m_H$  for the most massive associated particle (same as option -7).  $-8$  is the default value for **Process** 110, 111, 112 and 113. with scale multiplier 0.25.
- $\pm 9$ : If the scheme number is positive,  $\mu_{F,R} \propto \sqrt{q_J^2}$ , where  $J$  is the more massive associated particle. If the scheme number is negative and the matrix element treats an associated particle as massive (e.g.  $t$  in  $t + H$ ),  $\mu_{F,R} \propto m_J$ .
- **WidthScheme**: This option controls the width scheme in JHUGen. The options are 0 for fixed width, 1 for running width, and 2 for the complex pole scheme [7, 8]. 0 is the default option.
- **WriteFailedEvents**: In **ReadLHE** mode, events that fail in decay or that fail the lepton filter are by default not written to the LHE file. If this option is set to 1, they are written, but their weight is set to 0. If it is set to 2, they are written with a weight of zero and with no particles in the event. This option is useful if the same number of events are required to be in the input and the output.

Examples of running the generator:

- $gg$  production:

```
./JHUGen Collider=1 Process=0 VegasNc2=100000 PChannel=0 OffXVV=011 DecayMode1=0 \\  
DecayMode2=0 Unweighted=1 DataFile=ggHZZ41
```

- $ggH \rightarrow Z\gamma$

```
./JHUGen DecayMode1=0 DecayMode2=7 OffXVV=010 DataFile=ggHgammaZ21
```

- $ZH$  with hadronic  $Z$  decay (change **DecayMode1** for other  $Z$  decays; both  $pp$  and  $e^+e^-$  Collider options possible):

```
./JHUGen Collider=1 Process=50 DecayMode1=1 Unweighted=1 VegasNc2=100000 \\  
OffXVV=011 DataFile=ZH
```

- $WH$  with leptonic  $W$  decay (change **DecayMode1** for other  $W$  decays):

```
./JHUGen Collider=1 Process=50 DecayMode1=4 Unweighted=1 VegasNc2=100000 \\  
OffXVV=011 DataFile=WH
```

- VBF:

```
./JHUGen Collider=1 Process=60 Unweighted=1 VegasNc2=100000 OffXVV=011 DataFile=VBF
```

- $H + jj$ :

```
./JHUGen Collider=1 Process=61 Unweighted=1 VegasNc2=100000 OffXVV=011 DataFile=Hjj
```

- $H + j$ :

```
./JHUGen Collider=1 Process=62 Unweighted=1 VegasNc2=100000 OffXVV=011 DataFile=Hj
```

- $pp \rightarrow t\bar{t} + H$  with inclusive top decay (change DecayMode1,2 for specific  $tt$  decays):

```
./JHUGen Collider=1 Process=80 DecayMode1=11 DecayMode2=11 Unweighted=1 \\  
VegasNc2=100000 OffXVV=011 DataFile=ttH
```

- $pp \rightarrow b\bar{b} + H$ :

```
./JHUGen Collider=1 Process=90 Unweighted=1 VegasNc2=100000 OffXVV=011 DataFile=bbH
```

- $pp \rightarrow t + H$ ,  $t$  channel with inclusive top decay (change DecayMode1 for specific  $t$  decays; similar syntax for processes 111–113):

```
./JHUGen Collider=1 Process=110 DecayMode1=11 Unweighted=1 \\  
VegasNc2=100000 OffXVV=011 DataFile=tH_s
```

For generating Higgs decay in VBF,  $H + j(j)$ ,  $VH$ ,  $t\bar{t}H$ , or  $tH$  production modes by the JHU generator or NLO gluon fusion with another generator (e.g. POWHEG), use JHU generator in **ReadLHE** mode and specify the decay mode of interest (ZZ, WW, gam gam, Z gam), while the SM fermionic decays may be generated by Pythia without loss of generality.

## B. Configuration in parameter file

In the file `mod_Parameters.F90`, one does all the configuration of the couplings of the resonance. After modifying this file, one needs to recompile.

### 1. General parameters

- Switches:

- Each generation run is different when this is `.true.`

```
seed_random = .true.
```

- \* If `seed_random` is false, the seeds are set through  
`integer, public :: TheSeeds(0:20)`

- In the case when `PChannel=2` for a spin-2 resonance, the user can define an approximate ratio of the production of  $gg$  and  $q\bar{q}$  production.

```
fix_channels_ratio = .true.  
channels_ratio_fix = 0.25d0      ! desired ratio of N_qq/(N_qq+N_gg)
```

- For final states with a Z-boson decaying into  $f\bar{f}$ , intermediate off-shell photons can be included by switching  
`logical, public, parameter :: includeGammaStar = .false.`

to the value `.true..`

- \* In such case, a lower cut on the photon invariant mass has to be placed in order to avoid the collinear singularity. This cutoff parameter is controlled by

```
real(8),parameter :: MPhotonCutoff = 4d0*GeV.
```

- For  $VV$  decay (and similarly in  $t\bar{t}H$  production), by default the  $V$ 's are randomized so that, for example, `DecayMode1=5 DecayMode2=11` will produce all combinations that include at least one hadronic  $W$  decay (rather of specifically hadronic decay of the  $W^+$ ). This can be switched off by changing

```
logical, public, parameter :: RandomizeVV = .true.
```

to `.false..` In this case, `DecayMode1` will refer specifically to the  $W^+$  and `DecayMode2` to the  $W^-$ . For  $ZZ$  decay, this parameter only determines whether the decays of first and second  $Z$  written to the LHE file are randomized or not; in this case the only effect is the appearance of the output.

- When reading in LHE files, JHUGen determines the format by looking at the first lines of the first event. If this determination fails for any reason (for example, if different events are written in inconsistent formats), try changing

```
+logical, public, parameter :: UseUnformattedRead = .false.
```

to `.true..` However, this will noticeably slow down event generation in `ReadLHE` mode.

- For the generation of weighted events (command line `Unweighted=0`) an LHE output file is created if

```
logical, public, parameter :: writeWeightedLHE = .false.
```

is set to `.true..`

- Jet cuts:

```
real(8), public, parameter :: pTjetcut = 15d0*GeV      ! jet min pt
real(8), public, parameter :: Rjet = 0.3d0             ! jet deltaR, antikt algorithm
real(8), public, parameter :: mJJcut = 0d0*GeV         ! minimum mJJ for VBF, HJJ, bbH
```

All three cuts are used in processes 60 (VBF), 61 ( $H + jj$ ), 90 ( $bbH$ ), and also 80 ( $ttH$ ) if `m_Top` is set to be light ( $< 10\text{GeV}$ ). `pTjetcut` is also used in process 62 ( $H + j$ ) and processes 110–113 ( $t/\bar{t} + H$ ).

- Constants, more or less self-explanatory, including the masses of particles and width of Standard Model particles and the generated resonance, CKM matrix elements,  $Z$  and  $W$  branching fractions and scale factors for NLO QCD corrections ( $1 + \alpha_s/\pi$ ), and collider energies. They are documented in comments in `mod_Parameters.F90`.
- Resonance couplings to SM fields, described in detail in the next few sections

## 2. Spin-0 parameters

The `*hg*` parameters control the coupling of a spin-0 resonance to gluons in the production mechanism. In practice, the production parameters do not have a large effect since angular corrections from the production mechanism are lost for spinless particles. The `*hz*` parameters control the decay into  $Z$  and  $W$  bosons. One has the options to set the spin-0 couplings either from Eq.(9) or Eq.(11) from Ref. [2]. To switch between the two, use the parameter `generate_as`. We allow for  $q^2$  dependent form factors similar to those described in Ref. [3]:

$$\begin{aligned}
g_i^\Lambda(q_1, q_2) &= g_i' \frac{\Lambda_i^4}{(\Lambda_i^2 + |q_1^2|)(\Lambda_i^2 + |q_2^2|)} \\
&+ g_i'^2 \frac{(q_1^2 + q_2^2)}{\Lambda_i^2} + g_i'^3 \frac{(q_1^2 - q_2^2)}{\Lambda_i^2} + g_i'^4 \frac{(q_1 + q_2)^2}{\Lambda_Q^2} \\
&+ g_i'^5 \frac{((q_1^2)^2 + (q_2^2)^2)}{\Lambda_i^4} + g_i'^6 \frac{((q_1^2)^2 - (q_2^2)^2)}{\Lambda_i^4} + g_i'^7 \frac{q_1^2 q_2^2}{\Lambda_i^4} \\
g_i(q_1, q_2) &= g_i \delta_{i1} + (g_i^\Lambda(q_1, q_2) + g_i(1 - \delta_{i1})) \frac{\Lambda_{i1}^2 \Lambda_{i2}^2 \Lambda_{i3}^2}{(\Lambda_{i1}^2 + c_{i1}|q_1|^2)(\Lambda_{i2}^2 + c_{i2}|q_2|^2)(\Lambda_{i3}^2 + c_{i3}|q_1 + q_2|^2)}
\end{aligned}$$

The user has the option to choose between these functional forms, where the term multiplying  $g_i'$  corresponds to the full functional form and the  $g_i'' \dots g_i''''''$  correspond to an expansion in  $\Lambda^2$ . All parameters can be modified in `mod_Parameters.F90` by:

```
!-- parameters that define on-shell spin 0 coupling to SM fields, see note
logical, public, parameter :: generate_as = .false.
complex(8), public, parameter :: ahg1 = (1.0d0,0d0)
complex(8), public, parameter :: ahg2 = (0.0d0,0d0)
complex(8), public, parameter :: ahg3 = (0.0d0,0d0) ! pseudoscalar
```

```

complex(8), public, parameter :: ahz1 = (1.0d0,0d0)
complex(8), public, parameter :: ahz2 = (0.0d0,0d0) ! this coupling does not contribute for
                                                    ! gamma+gamma final states
complex(8), public, parameter :: ahz3 = (0.0d0,0d0) ! pseudoscalar

!-- parameters that define off-shell spin 0 coupling to SM fields, see note
complex(8), public, parameter :: ghg2 = (1.0d0,0d0)
complex(8), public, parameter :: ghg3 = (0.0d0,0d0)
complex(8), public, parameter :: ghg4 = (0.0d0,0d0) ! pseudoscalar
complex(8), public, parameter :: ghz1 = (2.0d0,0d0)
complex(8), public, parameter :: ghz2 = (0.0d0,0d0)
complex(8), public, parameter :: ghz3 = (0.0d0,0d0)
complex(8), public, parameter :: ghz4 = (0.0d0,0d0) ! pseudoscalar

!-- parameters that define q^2 dependent form factors
complex(8), public, parameter :: ghz1_prime = (0.0d0,0d0)
complex(8), public, parameter :: ghz1_prime2= (0.0d0,0d0)
complex(8), public, parameter :: ghz1_prime3= (0.0d0,0d0)
complex(8), public, parameter :: ghz1_prime4= (0.0d0,0d0)
complex(8), public, parameter :: ghz1_prime5= (0.0d0,0d0)
complex(8), public, parameter :: ghz1_prime6= (0.0d0,0d0)
complex(8), public, parameter :: ghz1_prime7= (0.0d0,0d0)

complex(8), public, parameter :: ghz2_prime = (0.0d0,0d0)
complex(8), public, parameter :: ghz2_prime2= (0.0d0,0d0)
complex(8), public, parameter :: ghz2_prime3= (0.0d0,0d0)
complex(8), public, parameter :: ghz2_prime4= (0.0d0,0d0)
complex(8), public, parameter :: ghz2_prime5= (0.0d0,0d0)
complex(8), public, parameter :: ghz2_prime6= (0.0d0,0d0)
complex(8), public, parameter :: ghz2_prime7= (0.0d0,0d0)

complex(8), public, parameter :: ghz3_prime = (0.0d0,0d0)
complex(8), public, parameter :: ghz3_prime2= (0.0d0,0d0)
complex(8), public, parameter :: ghz3_prime3= (0.0d0,0d0)
complex(8), public, parameter :: ghz3_prime4= (0.0d0,0d0)
complex(8), public, parameter :: ghz3_prime5= (0.0d0,0d0)
complex(8), public, parameter :: ghz3_prime6= (0.0d0,0d0)
complex(8), public, parameter :: ghz3_prime7= (0.0d0,0d0)

complex(8), public, parameter :: ghz4_prime = (0.0d0,0d0)
complex(8), public, parameter :: ghz4_prime2= (0.0d0,0d0)
complex(8), public, parameter :: ghz4_prime3= (0.0d0,0d0)
complex(8), public, parameter :: ghz4_prime4= (0.0d0,0d0)
complex(8), public, parameter :: ghz4_prime5= (0.0d0,0d0)
complex(8), public, parameter :: ghz4_prime6= (0.0d0,0d0)
complex(8), public, parameter :: ghz4_prime7= (0.0d0,0d0)

real(8),    public, parameter :: Lambda_z1 = 10000d0*GeV
real(8),    public, parameter :: Lambda_z2 = 10000d0*GeV
real(8),    public, parameter :: Lambda_z3 = 10000d0*GeV
real(8),    public, parameter :: Lambda_z4 = 10000d0*GeV
real(8),    public, parameter :: Lambda_Q  = 10000d0*GeV

integer,    public, parameter :: cz_q1sq = 0d0 ! Sign of q1,2,12**2 for the following Lambda's
integer,    public, parameter :: cz_q2sq = 0d0
integer,    public, parameter :: cz_q12sq = 0d0

real(8),    public, parameter :: Lambda_z11 = 100d0*GeV ! For Z1

```

```

real(8),    public, parameter :: Lambda_z21 = 100d0*GeV
real(8),    public, parameter :: Lambda_z31 = 100d0*GeV
real(8),    public, parameter :: Lambda_z41 = 100d0*GeV
real(8),    public, parameter :: Lambda_z12 = 100d0*GeV ! For Z2
real(8),    public, parameter :: Lambda_z22 = 100d0*GeV
real(8),    public, parameter :: Lambda_z32 = 100d0*GeV
real(8),    public, parameter :: Lambda_z42 = 100d0*GeV
real(8),    public, parameter :: Lambda_z10 = 100d0*GeV ! For the Higgs
real(8),    public, parameter :: Lambda_z20 = 100d0*GeV
real(8),    public, parameter :: Lambda_z30 = 100d0*GeV
real(8),    public, parameter :: Lambda_z40 = 100d0*GeV

```

If the switch `includeGammaStar` is set to `.true.` then intermediate off-shell photons are included for  $Z$  boson final states. Their couplings to the spin-0 resonance are controlled by separate parameters,

```

complex(8), public, parameter :: ghzgs2 = (0.00d0,0d0)
complex(8), public, parameter :: ghzgs3 = (0.00d0,0d0)
complex(8), public, parameter :: ghzgs4 = (0.00d0,0d0)
complex(8), public, parameter :: ghgs2 = (0.00d0,0d0)
complex(8), public, parameter :: ghgs3 = (0.00d0,0d0)
complex(8), public, parameter :: ghgs4 = (0.00d0,0d0)

```

where the first three correspond to  $Z\gamma^*$  couplings and the latter three corresponds to  $\gamma^*\gamma^*$  interactions. These two sets of parameters also control the coupling strength in final states with on-shell photons, i.e.  $Z\gamma$  and  $\gamma\gamma$ . The anomalous coupling involving the off-shell photon momentum (in  $\gamma^*Z$  interactions)

$$g'_1 \frac{q_\gamma^2}{\Lambda_2^2} m_Z^2 \epsilon_1^* \epsilon_2^*$$

is set by

```

complex(8), public, parameter :: ghzgs1_prime2= (0.0d0,0d0)
real(8),    public, parameter :: Lambda_zgs1 = 1000d0*GeV.

```

In the weak vector boson fusion process (VBF) we also allow for different  $ZZH$  and  $WWH$  couplings. Per default, they are assumed to be equal, set by

```

logical, public, parameter :: distinguish_HWWcouplings=.false.

```

If this value is set to `.true.`, their value will be used instead for the  $WWH$  interactions. Each `Lambda_z` and `cz_q1sq` parameter has a `Lambda_w` and `cw_q1sq` counterpart.

### 3. Spin-1 parameters

The parameters below represent the couplings given in Eq. (16) from Ref. [2]. The `*left*` and `*right*` parameters control the production of the spin-1 resonance while the `*_v` and `*_a` parameters control the decay.

```

!---parameters that define spin 1 coupling to SM fields, see note
complex(8), public, parameter :: zprime_qq_left = (1.0d0,0d0) ! see note Eq. (4)
complex(8), public, parameter :: zprime_qq_right = (0.0d0,0d0)
complex(8), public, parameter :: zprime_zz_v = (1.0d0,0d0)! =1 for JP=1-
complex(8), public, parameter :: zprime_zz_a = (0.0d0,0d0)! =1 for JP=1+

```

### 4. Spin-2 parameters

The `a*` parameters control the coupling of a spin-2 resonance to gluons in the production mechanism. The `b*` and `c*` parameters control the decay. One has the options to set the spin-2 couplings either from Eq.(18) or Eq.(19) from Ref. [2]. To switch between the two, use the parameter `generate_bis`.



```

logical, public, parameter :: generate_bis = .true.
logical, public, parameter :: use_dynamic_MG = .true. ! .true. (=default),
! the spin-2 resonance mass with  $MG^2=(p_1+p_2)^2$ , otherwise fixed at  $M_{\text{Reso}}^2$ .

complex(8), public, parameter :: a1 = (1.0d0,0d0)    ! g1 -- c.f. note
complex(8), public, parameter :: a2 = (0.0d0,0d0)    ! g2
complex(8), public, parameter :: a3 = (0.0d0,0d0)    ! g3
complex(8), public, parameter :: a4 = (0.0d0,0d0)    ! g4
complex(8), public, parameter :: a5 = (0.0d0,0d0)    ! pseudoscalar, g8

complex(8), public, parameter :: graviton_qq_left = (1.0d0,0d0)! graviton coupling to quarks
complex(8), public, parameter :: graviton_qq_right = (1.0d0,0d0)

complex(8), public, parameter :: b1 = (1.0d0,0d0)
complex(8), public, parameter :: b2 = (0.0d0,0d0)
complex(8), public, parameter :: b3 = (0.0d0,0d0)
complex(8), public, parameter :: b4 = (0.0d0,0d0)
complex(8), public, parameter :: b5 = (0.0d0,0d0)
complex(8), public, parameter :: b6 = (0.0d0,0d0)
complex(8), public, parameter :: b7 = (0.0d0,0d0)
complex(8), public, parameter :: b8 = (0.0d0,0d0)
complex(8), public, parameter :: b9 = (0.0d0,0d0)
complex(8), public, parameter :: b10 = (0.0d0,0d0)

complex(8), public, parameter :: c1 = (1.0d0,0d0)
complex(8), public, parameter :: c2 = (0.0d0,0d0)
complex(8), public, parameter :: c3 = (0.0d0,0d0)
complex(8), public, parameter :: c41 = (0.0d0,0d0)
complex(8), public, parameter :: c42 = (0.0d0,0d0)
complex(8), public, parameter :: c5 = (0.0d0,0d0)
complex(8), public, parameter :: c6 = (0.0d0,0d0)
complex(8), public, parameter :: c7 = (0.0d0,0d0)

```

### III. EXAMPLES

The below examples are not meant to be a complete set, but rather some interesting and relevant cases. In many cases, the example is not the only way to produce such a scenario.

#### A. $J^P = 0_m^+$ resonance, $X \rightarrow ZZ$ or $WW$

```

logical, public, parameter :: generate_as = .true.

complex(8), public, parameter :: ahg1 = (1.0d0,0d0)
complex(8), public, parameter :: ahg2 = (0.0d0,0d0)
complex(8), public, parameter :: ahg3 = (0.0d0,0d0)    ! pseudoscalar
complex(8), public, parameter :: ahz1 = (1.0d0,0d0)
complex(8), public, parameter :: ahz2 = (0.0d0,0d0)
complex(8), public, parameter :: ahz3 = (0.0d0,0d0)    ! pseudoscalar

```

#### B. $J^P = 0_m^-$ resonance, $X \rightarrow ZZ$ or $WW$

```

logical, public, parameter :: generate_as = .true.

complex(8), public, parameter :: ahg1 = (1.0d0,0d0)

```

```

complex(8), public, parameter :: ahg2 = (0.0d0,0d0)
complex(8), public, parameter :: ahg3 = (0.0d0,0d0) ! pseudoscalar
complex(8), public, parameter :: ahz1 = (0.0d0,0d0)
complex(8), public, parameter :: ahz2 = (0.0d0,0d0)
complex(8), public, parameter :: ahz3 = (1.0d0,0d0) ! pseudoscalar

```

**C.**  $J^P = 0_m^+$  resonance,  $X \rightarrow \gamma\gamma$

In practice, the example  $X \rightarrow \gamma\gamma$  from this section, Sec. IIIC and the next Sec. IIID are kinematically the same but are presented only to illustrate how one takes care of this final state.

```

logical, public, parameter :: generate_as = .false.

complex(8), public, parameter :: ghg2 = (1.0d0,0d0)
complex(8), public, parameter :: ghg3 = (0.0d0,0d0)
complex(8), public, parameter :: ghg4 = (0.0d0,0d0) ! pseudoscalar
complex(8), public, parameter :: ghgsgs2 = (1.0d0,0d0)
complex(8), public, parameter :: ghgsgs3 = (0.0d0,0d0)
complex(8), public, parameter :: ghgsgs4 = (0.0d0,0d0) ! pseudoscalar

```

**D.**  $J^P = 0_m^-$  resonance,  $X \rightarrow \gamma\gamma$

```

logical, public, parameter :: generate_as = .false.

complex(8), public, parameter :: ghg2 = (1.0d0,0d0)
complex(8), public, parameter :: ghg3 = (0.0d0,0d0)
complex(8), public, parameter :: ghg4 = (0.0d0,0d0) ! pseudoscalar
complex(8), public, parameter :: ghgsgs2 = (1.0d0,0d0)
complex(8), public, parameter :: ghgsgs3 = (0.0d0,0d0)
complex(8), public, parameter :: ghgsgs4 = (0.0d0,0d0) ! pseudoscalar

```

**E.**  $J^P = 2_m^+$  resonance,  $X \rightarrow ZZ$  or  $WW$  or  $\gamma\gamma$

```

complex(8), public, parameter :: a1 = (1.0d0,0d0) ! g1 -- c.f. draft
complex(8), public, parameter :: a2 = (0.0d0,0d0) ! g2
complex(8), public, parameter :: a3 = (0.0d0,0d0) ! g3
complex(8), public, parameter :: a4 = (0.0d0,0d0) ! g4
complex(8), public, parameter :: a5 = (0.0d0,0d0) ! pseudoscalar, g8
complex(8), public, parameter :: graviton_qq_left = (1.0d0,0d0)! graviton coupling to quarks
complex(8), public, parameter :: graviton_qq_right = (1.0d0,0d0)

```

```

logical, public, parameter :: generate_bis = .true.
logical, public, parameter :: use_dynamic_MG = .true.

```

```

complex(8), public, parameter :: b1 = (1.0d0,0d0)
complex(8), public, parameter :: b2 = (0.0d0,0d0)
complex(8), public, parameter :: b3 = (0.0d0,0d0)
complex(8), public, parameter :: b4 = (0.0d0,0d0)
complex(8), public, parameter :: b5 = (1.0d0,0d0)
complex(8), public, parameter :: b6 = (0.0d0,0d0)
complex(8), public, parameter :: b7 = (0.0d0,0d0)
complex(8), public, parameter :: b8 = (0.0d0,0d0)
complex(8), public, parameter :: b9 = (0.0d0,0d0)
complex(8), public, parameter :: b10 = (0.0d0,0d0)

```

## F. Cross-section calculation and fraction notation

For a vector boson coupling, we can represent the four independent parameters by two fractions ( $f_{g2}$  and  $f_{g4}$ ) and two phases ( $\phi_{g2}$  and  $\phi_{g4}$ ), defined for the  $HZZ$  and  $HWW$  couplings as follows (ignoring  $g_3$ )

$$f_{gi} = \frac{|g_i|^2 \sigma_i}{|g_1|^2 \sigma_1 + |g_2|^2 \sigma_2 + |g_4|^2 \sigma_4}; \quad \phi_{gi} = \arg\left(\frac{g_i}{g_1}\right).$$

In order to obtain the cross-sections  $\sigma_i$  corresponding to the  $g_i = 1$  coupling, generate large enough (e.g. VegasNc1=1000000, VegasNc2=50000000) number of weighted (**Unweighted=0**) with the corresponding couplings setup ( $g_i = 1$ ,  $g_{j \neq i} = 0$ ).

## G. LHAPDF

It is possible to interface to an LHAPDF setup instead of compiling with local PDF's. To accomplish this:

- In the makefile:
  - Set UseLHAPDF=Yes
  - Set MyLHADir to a directory with your LHAPDF setup. This can be in terms of environment variables; for example MyLHADir=\${LHAPDF\_DATA\_PATH}/../lib/.
- Ensure that \$LHAPDF\_DATA\_PATH and \$LD\_LIBRARY\_PATH are set (both when compiling and when running).
- Compile
- Run with the extra command line parameter LHAPDF specifying your PDF set's .info file. For example: LHAPDF=NNPDF30\_lo\_as\_0130/NNPDF30\_lo\_as\_0130.info

## IV. JHU GENERATOR MATRIX ELEMENTS (JHUGENMELA)

After extracting the code, you can go to the directory JHUGenMELA to find code for computing matrix elements directly. To compile the code, simply run `make`.

**Please take note: The setup is configured for gfort + gcc version 4.1.2 20080704 (Red Hat 4.1.2-50) and it is highly dependent on the compiler version. Please configure for your own setup accordingly.** (Using the `nm` command will help decipher the module names you will need)

Instructions for setting up the JHUGenMELA with MCFM are in the file JHUGenMELA/ggZZ\_MCFM/README. This C++ interface also covers the native matrix elements aforementioned through the wrapper class TEvtProb. The class currently includes the following calls:

- **TEvtProb**: Constructor with argument  $\sqrt{s}$  in units of GeV.
- **SetProcess**: Set the process to be used in the calculation of the ME
- **SetMatrixElement**: Set the matrix element (Analytical, MCFM or JHUGen)
- **SetProduction**: Set the production (as enumerated in the TVar class)
- **SetLeptonInterf**: Set whether lepton interference is included in decay MEs. By default, it is included for JHUGen decay MEs or MCFM  $q\bar{q}$  background MEs. It is not included in the other MCFM MEs.
- **ResetMCFM\_EWKParameters**: Reset the MCFM EWK scheme and its parameters. See MCFM manual for the details on the EWK scheme.
- **Set\_LHAGrid**: One-time call to setup the PDF path in case NNPDF 3.0 is used.

- **XsecCalc**: Calls to the decay MEs are handled through this function. Depending on the type of process, the self-defined coupling arrays may be ignored. Uses the following interfaced fortran subroutines:
  - "modhiggs\_\_evalamp\_gg\_h\_vv": Spin-0 matrix elements for  $gg$  initiated processes
  - "modzprime\_\_evalamp\_qqb\_zprime\_vv": Spin-1 matrix elements for  $q\bar{q}$  initiated processes
  - "modzprime\_\_evalamp\_zprime\_vv": Spin-1 matrix elements production-independent
  - "modgraviton\_\_evalamp\_qqb\_g\_vv": Spin-2 matrix elements for  $q\bar{q}$  initiated processes
  - "modgraviton\_\_evalamp\_gg\_g\_vv": Spin-2 matrix elements for  $gg$  initiated processes
  - "modgraviton\_\_evalamp\_g\_vv": Spin-2 matrix elements production-independent
- **XsecCalcXJJ**: Calls to VBF, and  $Hjj$  MEs are handled from this function. Depending on the production mode or the process, these arrays may be ignored.
  - "modhiggsjj\_\_evalamp\_wbfh": Spin-0 matrix element for on-shell  $VBF$  production
  - "modhiggsjj\_\_evalamp\_sbfb": Spin-0 matrix element for on-shell  $H + JJ$  QCD production
- **XsecCalcXJ**: Call to the JHUGen  $Hj$  ME is handled through this routine.
  - "modhiggsj\_\_evalamp\_hj": Spin-0 matrix element for on-shell  $H + J$  QCD production
- **XsecCalc\_VX**: Call to the JHUGen  $VH$  ME is handled from this routine.
  - "modvhiggs\_\_evalamp\_vhiggs": Spin-0 matrix element for on-shell  $VH$  production
- **XsecCalc\_TTX**: Call to the  $t\bar{t}H$  ME is handled through this routine.
  - "modttbhiggs\_\_evalxsec\_pp\_ttbb": Spin-0 matrix element for on-shell  $t\bar{t}H$  production
  - "modttbhiggs\_\_evalxsec\_pp\_bbbh": Spin-0 matrix element for on-shell  $b\bar{b}H$  production
- **SetHiggsMass**: This routine changes the Higgs mass and width used in the MCFM calculations.

The inputs are usually the 4-vectors of the incoming patrons and outgoing particles in the CM frame of the object  $X$ . In addition the mass and width of the resonance are required as well as the ID of the outgoing particles. Finally the last set of inputs are the couplings themselves. They are arrays for parameters for a given spin hypothesis which mirror the parameters configurable in `mod_Parameters.F90`. Exemplary array initialization can be found in `testprogram.c` for the native matrix elements or `testME.C` for the interface with MCFM. For the interface, you can also see the beginning declarations in `TVar.hh` for the list of enumerated variables, and `testME.C` for example calls (eg. array filling, assignment of momenta, and passing the arguments to these routines).

## V. RELEASE NOTES

In going from v6.7.8 to v6.8.4, the updates are as follows:

- Added running renormalization scale and generalized the running scales
- Added more options for the Higgs mass shape
- Improved LHE reading and writing

In going from v6.2.8 to v6.7.8, the updates are as follows:

- Added running factorization scale ( $\mu_F = m_{H^*}/2$ ) in spin-0,1,2 decays
- Enabled identical  $4\nu$  and  $4q$  final state interference in  $ZZ$  decay
- Faster VBF and  $Hjj$  event generation with deterministic jet flavor assignment
- $VH$  code clean-up
- Update of the CKM matrix and of hadronic  $W$  decay

- New processes 110–113 for  $t/\bar{t} + H$  production
- More flexible lepton filter

In going from v5.6.3 to v6.2.8, the updates are as follows:

- Flexible LHE reading process for compatibility with more generators
- Small bugfixes

In going from v5.2.5 to v5.6.3, the updates are as follows:

- Add `Process=90` for  $bbH$  production
- Add lepton filtering option
- Allow  $W$  from  $ttH$  to decay to any decay mode
- Allow  $W$  to decay to off-diagonal elements of the CKM matrix
- Add support for LHAPDF linking
- Fixes for LHE printout in  $VBF$ ,  $Hjj$ , and  $VH$

In going from v4.8.1 to v5.2.5, the updates are as follows:

- Add `Process=80` for  $ttH$  production, with optional top decays
- Add support for NNPDF
- Make `DecayMode1`  $\neq$  `DecayMode2` equivalent to generating everything and then filtering
- Add option for randomizing the  $V$ 's in  $HVV$  decays
- Fixes for smoother reading of LHE files: mother assignment and invariant mass for all intermediate particles
- Add `ConvertLHE` option for converting VH decay to any `DecayMode`
- In `ReadLHE` and `ConvertLHE`, preserve comments and optional tags from the input LHE

In going from v4.5.2 to v4.8.1, the updates are as follows:

- More flexibility for  $q^2$ -dependent form factors
- Separate couplings for ZZH and WWH in weak boson fusion
- Add new process:  $pp \rightarrow H + \text{jet}$  (`Process=62`)
- Extended LHE output format to allow for more digits
- MCFM plug-in for anomalous couplings in off-shell Higgs boson production in  $gg \rightarrow ZZ$
- Synchronize JHUGenMELA with MCFM library v6.8
- JHUGenMELA: extended MCFM  $ggHZZ$  matrix elements by anomalous couplings
- JHUGenMELA: add matrix elements for  $H + \text{jet}$  and  $V + H$

In going from v4.3.2 to v4.5.2, the updates are as follows:

- Add an option of intermediate photons for the modes with Z-bosons
- More flexibility for  $q^2$ -dependent form factors
- Option of hadronic branching rescaling (NLO QCD corrections) for inclusive decays
- Synchronize JHUGenMELA with the generator and with MCFM library v6.7

In going from v4.2.1 to v4.3.2, the updates are as follows:

- Update LHE file format and index of partons
- Improve log printout
- Update ReadLHE mode:  $H \rightarrow Z\gamma$  output and more flexible input
- $VH$  production (replaces beta version)
- More flexibility for  $q^2$ -dependent form factors
- Tune  $q^2$ -dependence of couplings for some of the spin-2<sub>h</sub> models
- Synchronize JHUGenMELA with the generator

In going from v4.0.x to v4.2.x, the updates are as follows:

To JHUGenerator:

- Fix BR in "all" decay mode
- Updates to LHE output
- Option to print out CS<sub>max</sub>, output for g' and Lambdas
- Introduction of AnalyticMELA for  $ee \rightarrow ZH$  and  $pp \rightarrow ZH$  and analytic parton distribution functions

In going from v3.1.x to v4.0.x, the updates are as follows:

To JHUGenerator:

- Addition of VBF and Hjj process channels
- Possibility to read in VBF LHE event files

To JHUGenMELA:

- Interface with the MCFM program for ggZZ process
- Matrix elements for VBF and Hjj processes

In going from v2.2.6 to v3.1.8, the updates are as follows:

To JHUGenerator:

- Capability reading LHE files with Higgs boson production, allows NLO production of spin-0;
- Extended the list of final state combinations;
- Log messages, the file headers, and minor cleanup.
- Updates to deal with non-zero lepton masses, the file format, and adjust default settings (e.g. lepton interference applied by default and can be configured in command line)

To JHUGenMELA:

- Production-independent JHUGenMELA for spin-0, 1, 2;
- Complex couplings in JHUGenMELA input.

In going from v2.2.3 to v2.2.6, the updates are as follows:

- A small fix which corrects the *relative fraction* between the  $2e2\mu$  and  $4e/4\mu$  channels when using interference
- beta version is still under development
- $q\bar{q} \rightarrow$  spin-2 production is more safely performed with settings `PChannel = 2` and  $q\bar{q}$  fraction = 1.

In going from v2.1.3 to v2.2.3, the updates are as follows:

- Fix interference and randomization in the *beta* version

- Add the JHUGenMELA modules
- Small change for compilation on Mac OSX platforms
- Fix for tau masses in  $W$  decays

In going from v2.0.2 to v2.1.x, the updates are as follows:

- Histograms are written in file (default: ./data/output.dat) and no longer on the screen. How to understand the histogram data and how to plot is briefly described in the output.dat file.
- Added tau masses
- Added lepton interference in the ZZ4l final state
- Added switch `generate_as` to choose couplings in spin-0 case (works for on- and off-shell resonance). The default is ".false.".
- Added the possibility to change graviton-quark couplings. The new parameters are `graviton_qq_left`, `graviton_qq_right` and correspond to  $0.5*(1-\gamma^5)$  and  $0.5*(1+\gamma^5)$  helicity projectors, respectively. Up to now the coupling was always vector-like. This is also the new default, `graviton_qq_left = graviton_qq_right = 1`.
- The random seed is now fixed with gfortran.
- The call `./JHUGen help` prints out all available command line options
- Added new command line option `"Unweighted=0 or 1"` (default is 1)

## APPENDIX A: SPECIFIC CONFIGURATIONS

We define configurations for certain models which are defined in Table 1 of [2].

### 1. "SM-like spin-zero", $0^+$

```
!-- parameters that define on-shell spin 0 coupling to SM fields, see note
logical, public, parameter :: generate_as = .false.
complex(8), public, parameter :: ahg1 = (1.0d0,0d0)
complex(8), public, parameter :: ahg2 = (0.0d0,0d0)
complex(8), public, parameter :: ahg3 = (0.0d0,0d0) ! pseudoscalar
complex(8), public, parameter :: ahz1 = (1.0d0,0d0)
complex(8), public, parameter :: ahz2 = (0.0d0,0d0) ! this coupling does not contribute for gamma+gamma final states
complex(8), public, parameter :: ahz3 = (0.0d0,0d0) ! pseudoscalar

!-- parameters that define off-shell spin 0 coupling to SM fields, see note
complex(8), public, parameter :: ghg2 = (1.0d0,0d0)
complex(8), public, parameter :: ghg3 = (0.0d0,0d0)
complex(8), public, parameter :: ghg4 = (0.0d0,0d0) ! pseudoscalar
complex(8), public, parameter :: ghz1 = (1.0d0,0d0)
complex(8), public, parameter :: ghz2 = (0.0d0,0d0)
complex(8), public, parameter :: ghz3 = (0.0d0,0d0)
complex(8), public, parameter :: ghz4 = (0.0d0,0d0) ! pseudoscalar
```

### 2. "Higher order spin-zero", $0_h^+$

```
!-- parameters that define on-shell spin 0 coupling to SM fields, see note
logical, public, parameter :: generate_as = .false.
complex(8), public, parameter :: ahg1 = (1.0d0,0d0)
complex(8), public, parameter :: ahg2 = (0.0d0,0d0)
complex(8), public, parameter :: ahg3 = (0.0d0,0d0) ! pseudoscalar
complex(8), public, parameter :: ahz1 = (1.0d0,0d0)
complex(8), public, parameter :: ahz2 = (0.0d0,0d0) ! this coupling does not contribute for gamma+gamma final states
complex(8), public, parameter :: ahz3 = (0.0d0,0d0) ! pseudoscalar

!-- parameters that define off-shell spin 0 coupling to SM fields, see note
complex(8), public, parameter :: ghg2 = (1.0d0,0d0)
complex(8), public, parameter :: ghg3 = (0.0d0,0d0)
complex(8), public, parameter :: ghg4 = (0.0d0,0d0) ! pseudoscalar
complex(8), public, parameter :: ghz1 = (0.0d0,0d0)
complex(8), public, parameter :: ghz2 = (1.0d0,0d0)
complex(8), public, parameter :: ghz3 = (0.0d0,0d0)
complex(8), public, parameter :: ghz4 = (0.0d0,0d0) ! pseudoscalar
```

### 3. "Pseudoscalar spin-zero", $0^-$

```
!-- parameters that define on-shell spin 0 coupling to SM fields, see note
logical, public, parameter :: generate_as = .false.
complex(8), public, parameter :: ahg1 = (1.0d0,0d0)
complex(8), public, parameter :: ahg2 = (0.0d0,0d0)
complex(8), public, parameter :: ahg3 = (0.0d0,0d0) ! pseudoscalar
complex(8), public, parameter :: ahz1 = (1.0d0,0d0)
complex(8), public, parameter :: ahz2 = (0.0d0,0d0) ! this coupling does not contribute for gamma+gamma final states
complex(8), public, parameter :: ahz3 = (0.0d0,0d0) ! pseudoscalar

!-- parameters that define off-shell spin 0 coupling to SM fields, see note
complex(8), public, parameter :: ghg2 = (0.0d0,0d0)
complex(8), public, parameter :: ghg3 = (0.0d0,0d0)
complex(8), public, parameter :: ghg4 = (1.0d0,0d0) ! pseudoscalar
complex(8), public, parameter :: ghz1 = (0.0d0,0d0)
complex(8), public, parameter :: ghz2 = (0.0d0,0d0)
complex(8), public, parameter :: ghz3 = (0.0d0,0d0)
complex(8), public, parameter :: ghz4 = (1.0d0,0d0) ! pseudoscalar
```



#### 4. "Vector spin-one", $1^-$

```
!---parameters that define spin 1 coupling to SM fields, see note
complex(8), public, parameter :: zprime_qq_left = (1.0d0,0d0)
complex(8), public, parameter :: zprime_qq_right = (0.0d0,0d0)
complex(8), public, parameter :: zprime_zz_v = (1.0d0,0d0)! =1 for JP=1-
complex(8), public, parameter :: zprime_zz_a = (0.0d0,0d0)! =1 for JP=1+
```

#### 5. "Pseudovector spin-one", $1^+$

```
!---parameters that define spin 1 coupling to SM fields, see note
complex(8), public, parameter :: zprime_qq_left = (1.0d0,0d0)
complex(8), public, parameter :: zprime_qq_right = (0.0d0,0d0)
complex(8), public, parameter :: zprime_zz_v = (0.0d0,0d0)! =1 for JP=1-
complex(8), public, parameter :: zprime_zz_a = (1.0d0,0d0)! =1 for JP=1+
```

#### 6. "Minimal Graviton, spin-two", $2^+$

N.B. If an exclusive production mode is desired (e.g.  $q\bar{q}$  or  $gg$ ), this is handled at command-line configuration level via the `PChannel` variable.

```
!-- parameters that define spin 2 coupling to SM fields, see note
! minimal coupling corresponds to a1 = b1 = b5 = 1 everything else 0
complex(8), public, parameter :: a1 = (1.0d0,0d0) ! g1 -- c.f. draft
complex(8), public, parameter :: a2 = (0.0d0,0d0) ! g2
complex(8), public, parameter :: a3 = (0.0d0,0d0) ! g3
complex(8), public, parameter :: a4 = (0.0d0,0d0) ! g4
complex(8), public, parameter :: a5 = (0.0d0,0d0) ! pseudoscalar, g8
complex(8), public, parameter :: graviton_qq_left = (1.0d0,0d0)! graviton coupling to quarks
complex(8), public, parameter :: graviton_qq_right = (1.0d0,0d0)

!-- see mod_Graviton
logical, public, parameter :: generate_bis = .true.
logical, public, parameter :: use_dynamic_MG = .true.

complex(8), public, parameter :: b1 = (1.0d0,0d0) ! all b' below are g's in the draft
complex(8), public, parameter :: b2 = (0.0d0,0d0)
complex(8), public, parameter :: b3 = (0.0d0,0d0)
complex(8), public, parameter :: b4 = (0.0d0,0d0)
complex(8), public, parameter :: b5 = (1.0d0,0d0)
complex(8), public, parameter :: b6 = (0.0d0,0d0)
complex(8), public, parameter :: b7 = (0.0d0,0d0)
complex(8), public, parameter :: b8 = (0.0d0,0d0)
complex(8), public, parameter :: b9 = (0.0d0,0d0)
complex(8), public, parameter :: b10 = (0.0d0,0d0) ! this coupling does not contribute for gamma+gamma final states

complex(8), public, parameter :: c1 = (1.0d0,0d0)
complex(8), public, parameter :: c2 = (0.0d0,0d0)
complex(8), public, parameter :: c3 = (0.0d0,0d0)
complex(8), public, parameter :: c41 = (0.0d0,0d0)
complex(8), public, parameter :: c42 = (0.0d0,0d0)
complex(8), public, parameter :: c5 = (0.0d0,0d0)
complex(8), public, parameter :: c6 = (0.0d0,0d0)
complex(8), public, parameter :: c7 = (0.0d0,0d0)
```

#### 7. "Higher order Graviton, spin-two", $2_h^+$

```
!-- parameters that define spin 2 coupling to SM fields, see note
! minimal coupling corresponds to a1 = b1 = b5 = 1 everything else 0
complex(8), public, parameter :: a1 = (0.0d0,0d0) ! g1 -- c.f. draft
complex(8), public, parameter :: a2 = (0.0d0,0d0) ! g2
complex(8), public, parameter :: a3 = (0.0d0,0d0) ! g3
```

```

complex(8), public, parameter :: a4 = (1.0d0,0d0)      ! g4
complex(8), public, parameter :: a5 = (0.0d0,0d0)      ! pseudoscalar, g8
complex(8), public, parameter :: graviton_qq_left  = (1.0d0,0d0)! graviton coupling to quarks
complex(8), public, parameter :: graviton_qq_right = (1.0d0,0d0)

!-- see mod_Graviton
logical, public, parameter :: generate_bis = .true.
logical, public, parameter :: use_dynamic_MG = .true.

complex(8), public, parameter :: b1 = (0.0d0,0d0)      ! all b' below are g's in the draft
complex(8), public, parameter :: b2 = (0.0d0,0d0)
complex(8), public, parameter :: b3 = (0.0d0,0d0)
complex(8), public, parameter :: b4 = (1.0d0,0d0)
complex(8), public, parameter :: b5 = (0.0d0,0d0)
complex(8), public, parameter :: b6 = (0.0d0,0d0)
complex(8), public, parameter :: b7 = (0.0d0,0d0)
complex(8), public, parameter :: b8 = (0.0d0,0d0)
complex(8), public, parameter :: b9 = (0.0d0,0d0)
complex(8), public, parameter :: b10=(0.0d0,0d0) ! this coupling does not contribute for gamma+gamma final states

complex(8), public, parameter :: c1 = (1.0d0,0d0)
complex(8), public, parameter :: c2 = (0.0d0,0d0)
complex(8), public, parameter :: c3 = (0.0d0,0d0)
complex(8), public, parameter :: c41=(0.0d0,0d0)
complex(8), public, parameter :: c42=(0.0d0,0d0)
complex(8), public, parameter :: c5 = (0.0d0,0d0)
complex(8), public, parameter :: c6 = (0.0d0,0d0)
complex(8), public, parameter :: c7 = (0.0d0,0d0)

```

## 8. "Higher order Graviton, spin-two", $2_h^-$

```

!-- parameters that define spin 2 coupling to SM fields, see note
! minimal coupling corresponds to a1 = b1 = b5 = 1 everything else 0
complex(8), public, parameter :: a1 = (0.0d0,0d0)      ! g1 -- c.f. draft
complex(8), public, parameter :: a2 = (0.0d0,0d0)      ! g2
complex(8), public, parameter :: a3 = (0.0d0,0d0)      ! g3
complex(8), public, parameter :: a4 = (0.0d0,0d0)      ! g4
complex(8), public, parameter :: a5 = (1.0d0,0d0)      ! pseudoscalar, g8
complex(8), public, parameter :: graviton_qq_left  = (1.0d0,0d0)! graviton coupling to quarks
complex(8), public, parameter :: graviton_qq_right = (1.0d0,0d0)

!-- see mod_Graviton
logical, public, parameter :: generate_bis = .true.
logical, public, parameter :: use_dynamic_MG = .true.

complex(8), public, parameter :: b1 = (0.0d0,0d0)      ! all b' below are g's in the draft
complex(8), public, parameter :: b2 = (0.0d0,0d0)
complex(8), public, parameter :: b3 = (0.0d0,0d0)
complex(8), public, parameter :: b4 = (0.0d0,0d0)
complex(8), public, parameter :: b5 = (0.0d0,0d0)
complex(8), public, parameter :: b6 = (0.0d0,0d0)
complex(8), public, parameter :: b7 = (0.0d0,0d0)
complex(8), public, parameter :: b8 = (1.0d0,0d0)
complex(8), public, parameter :: b9 = (0.0d0,0d0)
complex(8), public, parameter :: b10=(0.0d0,0d0) ! this coupling does not contribute for gamma+gamma final states

complex(8), public, parameter :: c1 = (1.0d0,0d0)
complex(8), public, parameter :: c2 = (0.0d0,0d0)
complex(8), public, parameter :: c3 = (0.0d0,0d0)
complex(8), public, parameter :: c41=(0.0d0,0d0)
complex(8), public, parameter :: c42=(0.0d0,0d0)
complex(8), public, parameter :: c5 = (0.0d0,0d0)
complex(8), public, parameter :: c6 = (0.0d0,0d0)
complex(8), public, parameter :: c7 = (0.0d0,0d0)

```

- 
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