Documentation for the $t\bar{t}$ bound states UFO

Claudio Severi, 16/7/2024

This model has been developed following Section 4.1 of `arXiv:2401.08751 [hep-ph]` and Section 4.3 of `arXiv:2404.08049 [hep-ph]`.

The UFO contains a copy of the usual SM UFO at LO, with the following changes:

- Two new particles have been included, `eta`, with PDG code 6001, corresponding to the $1S0$ pseudoscalar resonance that can be produced in a pp collider, and `jpsi`, with PDG code 6003, corresponding to the $3S1$ vector resonance reachable from e^+e^- collisions.

- The new vertices with η and J/ψ are:

$$(\,g\,g\,\eta\,) \quad \text{production } \eta \text{ from gluon fusion,} \tag{1}$$
$$(\,\eta\,t\,\bar{t}\,) \quad \text{decay of } \eta \text{ into tops,} \tag{2}$$
$$(\,e^+\,e^-\,J/\psi\,) \quad \text{production of } J/\psi \text{ from electron-positron,} \tag{3}$$
$$(\,J/\psi\,t\,\bar{t}\,) \quad \text{decay of } J/\psi \text{ into tops.} \tag{4}$$

  For the $(\,g\,g\,\eta\,)$ vertex, I have hard–coded the full triangle loop of top quarks (same as $gg \to H$) as an effective ggH vertex, so that one can generate for example:

```
g g > eta > t t~
```

  and obtain the full one-loop amplitude. The Feynman diagram produced in `mg5` will show a ggH vertex, but actually the full loop amplitude will be there.

- The bound states are given a mass, available in the parameter card. The bound state mass should be set to around:

$$m = 2m_t - (\text{a few})\ \text{GeV}. \tag{5}$$

  Bound states also have a decay width, that in practice will be very close to:

$$\Gamma = 2\Gamma_t. \tag{6}$$

  I normally use $m = 343\,\text{GeV}$ and $\Gamma = 3\,\text{GeV}$, but one can try to vary both parameters within some ranges.

- Both bound states are given a parameter, called `cy` and available in the parameter card, that parameterizes the strength of their interaction with bare top quarks. The coupling should be tuned to reproduce the total rate for producing the bound state that comes from NR-QCD calculations.

  For the η resonance at the LHC a reasonable value may be around $c_y = 9.1 \cdot 10^{-3}$, which leads to a total rate of $\sigma(gg \to \eta) \sim 3.5\,\text{pb}$, but again you can try some variation. Keep in mind that $\sigma(gg \to \eta) \propto c_y^4$ so small changes to c_y are enough to move the total rate significantly.

- In QCD the η resonance is a pseudoscalar, $\alpha = \pi/2$ in Eq.(4.1) of `2401.08751`, but I made the value of α a parameter, for generality. In the UFO it is called `alphay`, and can be set to any number between 0 (scalar resonance) and $\pi/2$ (pseudoscalar).

Note 1: The evaluation of the effective ggH vertex needs a small change in the process folder. In the files:

```
(process)/Source/DHELAS/GGH3_3.f
(process)/Source/DHELAS/GGH5_3.f
```

replace:

```
SQRT(DBLE( ... ))     ->     SQRT(...)
LOG(DBLE( ... ))      ->     LOG(...)
```

This is to ensure the imaginary part of the loop is evaluated properly. The replacement needs to be done once, after the process has been generated and before any runs. (It won't run if you don't do it, so it's easy to notice.) Once the change is done, recompile the `DHELAS` folder by running

```
make
```

inside of it.

Note 2: To reproduce best the NR-QCD calculations, see Figure 9 of `2404.08049`, it is actually better to allow $t\bar{t}$ resonances to decay to *on-shell* tops, instead of a pair where one top is slightly off-shell. My understanding is that, when the bound state is physically broken, its binding energy becomes available to the system and it is sufficient to send both tops on shell; we should simulate this effect in the MC.

There are a number of ways to have the resonances decay into an on-shell top pair:

1. Use as top mass some number $m_t \lesssim m_\eta/2$, to make the on-shell decay kinematically possible. Using $m_t = m_\eta/2$ is usually called *1S mass scheme*, see `hep-ph/0107144`.

2. Generate production and decay in `mg5`, and later reweight the events to remove the off-shellness of tops. The simplest way is to rescale the weight of all events by:

$$w \to w \times \frac{|p_t^2 - m_t^2 + i m_t \Gamma_t|^2}{|i m_t \Gamma_t|^2} \, \frac{|p_{\bar{t}}^2 - m_t^2 + i m_t \Gamma_t|^2}{|i m_t \Gamma_t|^2}. \tag{7}$$

   This basically replaces both top propagator denominators with the denominators of on-shell particles: $1/(p^2 - m^2 + i m\Gamma) \to 1/(i m \Gamma)$. It is rough but does the job, you can come up with something else of course.