Release Note for `HiggsSignals-1.3`

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In this note we briefly describe a new method to evaluate the χ^2 contribution from Higgs mass observables, as implemented in `HiggsSignals` [1, 2] version 1.3. An example is provided and information about newly available options is given.

1 Changes in `HiggsSignals-1.3`

1.1 A revamped χ^2 contribution from the Higgs mass observables

Thus far, in the case that multiple Higgs bosons are assigned to a mass-sensitive peak observable, each Higgs boson mass gave rise to a χ^2 contribution, i.e. we had

$$\chi_m^2 = \sum_{\text{assigned Higgses } i} \chi_{m,i}^2. \tag{1}$$

There are a few conceptual problems with this. Firstly, this approach is independent of the signal rates of the Higgses within the experimental analysis. For instance, in the limit that one Higgs boson does not contribute to the signal at all ($\mu \to 0$), its mass will still give rise to a χ^2 contribution. This is unphysical. Secondly, a statistical problem arises when several χ^2 contributions arise from the same observable.

In `HiggsSignals-1.3` we introduce a much more physically motivated and consistent algorithm to approach this problem. The idea arises from the fact that two (or more) overlapping Gaussian-like signals will approximately form a new Gaussian-like signal distribution enveloping the two (or more) signals, if the mass resolution is not good enough to resolve the two (or more) peaks. The position of this enveloping Gaussian peak and its (1σ) uncertainty are then approximately given by a signal-strength average of the masses and mass uncertainties of the individual signals,

$$\overline{m}_i = \frac{\sum_\alpha \mu_\alpha^i m_\alpha}{\sum_\alpha \mu_\alpha^i}, \qquad \overline{\Delta m}_i = \frac{\sum_\alpha \mu_\alpha^i \Delta m_\alpha}{\sum_\alpha \mu_\alpha^i}, \tag{2}$$

respectively. Here, α runs over all assigned Higgs bosons, and i denotes the index of the peak observable. These averaged quantities now enter the χ^2 test against the Higgs mass measurement, and give rise to only *one* χ^2 contribution.

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In the case of a *Gaussian* pdf (`pdf=2`), the theoretical mass uncertainties are still treated as fully correlated uncertainties among the peak observables i and j, if the same Higgs boson h_α has been assigned (denoted by the symbol '$\bowtie$' below). The diagonal and off-diagonal entries in the covariance matrix are then given by

$$\mathrm{cov}_{ii} = (\Delta\hat{m}_i)^2 + (\overline{\Delta m_i})^2, \tag{3}$$

$$\mathrm{cov}_{ij} = \sum_{\alpha\,\bowtie\,i,j} \frac{\mu_\alpha^i}{\mu_{\mathrm{tot}}^i}\frac{\mu_\alpha^j}{\mu_{\mathrm{tot}}^j}\overline{\Delta m_i}\,\overline{\Delta m_j}, \tag{4}$$

Here, $\hat{m}_i$ and $\Delta\hat{m}_i$ are the measured Higgs mass and its experimental uncertainty, respectively, in the peak observable i. μ_α^i is the SM-normalized signal rate of Higgs boson h_α in this observable, and $\mu_{\mathrm{tot}}^i = \sum_\alpha \mu_\alpha^i$.

Now, there arises another complication. In the formulation outlined above, a combination of a 120 GeV and 130 GeV Higgs boson with equal signal strength would yield the same χ^2 contribution as if both Higgs bosons were sitting at 125 GeV. If the mass resolution is very poor, this might be acceptable, however, in general, the first case should receive a penalty which depends on the experimental mass resolution, theoretical mass uncertainties and the relative contribution of each Higgs boson to the signal. We therefore introduce another χ^2 contribution for the mass separation of the assigned Higgs bosons in a peak observable i, which reads

$$\chi^2_{\mathrm{sep},i} = \sum_\alpha \frac{\mu_\alpha^i}{\mu_{\mathrm{total}}^i}\begin{cases} 0 & \text{if } |m_\alpha - \overline{m}| \leq \Delta m_\alpha + \Delta\hat{m}_i, \\ \infty & \text{else,}\end{cases} \tag{5}$$

in case of a box-shaped Higgs mass pdf (`pdf=1`),

$$\chi^2_{\mathrm{sep},i} = \sum_\alpha \frac{\mu_\alpha^i}{\mu_{\mathrm{total}}^i}\frac{(m_\alpha - \overline{m})^2}{\Delta m_\alpha^2 + \Delta\hat{m}_i^2} \tag{6}$$

for the choice of a Gaussian Higgs mass pdf (`pdf=2`), and

$$\chi^2_{\mathrm{sep},i} = \sum_\alpha \frac{\mu_\alpha^i}{\mu_{\mathrm{total}}^i}\begin{cases} \frac{(m_\alpha + \Delta m_\alpha - \overline{m}^i)^2}{(\Delta\hat{m}_i)^2}, & \text{if } m_\alpha + \Delta m_\alpha < \overline{m}^i, \\ \frac{(m_\alpha - \Delta m_\alpha - \overline{m}^i)^2}{(\Delta\hat{m}_i)^2}, & \text{if } m_\alpha - \Delta m_\alpha > \overline{m}^i, \\ 0 & \text{else,}\end{cases} \tag{7}$$

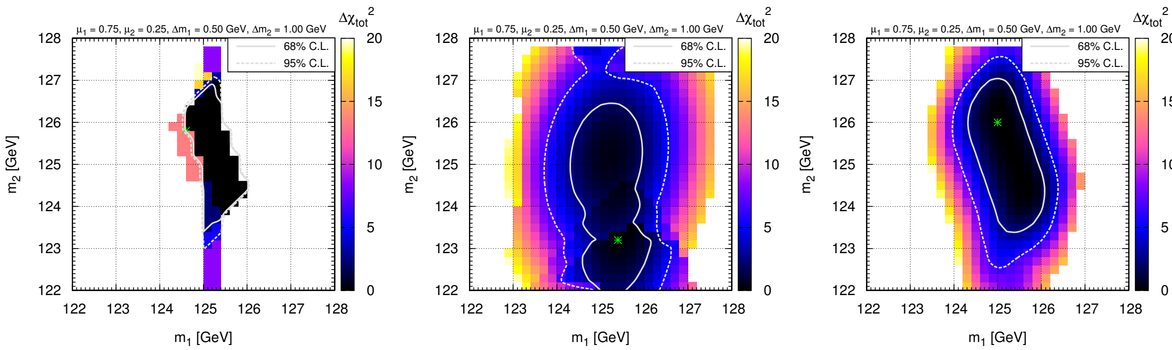
for a box-Gaussian Higgs mass pdf (`pdf=3`). The total χ^2 contribution from the Higgs mass is then simply given by the averaged mass χ^2 and the mass separation χ^2. It is obvious from the signal strength weight factor that in the limit $\mu_\alpha^i \to 0$, the Higgs boson h_α does not contribute to the mass χ^2 contribution of the peak observable i.

We show an example of this new χ^2 evaluation in Fig. 1 for two Higgs bosons with variable masses, signal rates $\mu_1 = 0.75$, $\mu_2 = 0.25$ and theoretical mass uncertainties $\Delta m_1 = 0.5$ GeV, $\Delta m_2 = 1.0$ GeV, respectively. The scan is performed using the observable set '`latestresults-1.3.0-LHCinclusive`', which is provided with `HiggsSignals-1.3`. The Higgs mass observables are

$$\hat{m}^{\gamma\gamma}_{\mathrm{ATLAS}} = (125.98 \pm 0.50)\ \mathrm{GeV}, \qquad \hat{m}^{ZZ}_{\mathrm{ATLAS}} = (124.51 \pm 0.52)\ \mathrm{GeV}, \tag{8}$$

$$\hat{m}^{\gamma\gamma}_{\mathrm{CMS}} = (124.70 \pm 0.34)\ \mathrm{GeV}, \qquad \hat{m}^{ZZ}_{\mathrm{CMS}} = (125.63 \pm 0.45)\ \mathrm{GeV}. \tag{9}$$

We furthermore provide a new example program



(a) Box pdf. (b) Gaussian pdf. (c) Box+Gaussian pdf.

Figure 1: Example of the revamped Higgs mass χ^2 contribution, for two Higgs bosons with signal rates $\mu_1 = 0.75$, $\mu_2 = 0.25$ and theoretical mass uncertainties $\Delta m_1 = 0.5$ GeV, $\Delta m_2 = 1.0$ GeV, respectively. The results for the three pdf choices (box, Gaussian, box+Gaussian) are shown. This figure is produced by the new example program `HS_2Higgses.f90`.

```
example_programs/HS_2Higgses.f90
```

that runs this example.

This new algorithm is used by default. If the user wishes to use the old algorithm of `HiggsSignals` version ≤ 1.2, the flag

```
logical :: useaveragemass = .False.
```

needs to be set in `usefulbits_HS.f90`.

1.2 Other developments

In general, in the peak-centered χ^2 method the (SM normalized) signal rates given as the user input and the measured (SM normalized) signal rates provided by the experiments are given at *different* mass positions (except in the special case where the predicted Higgs mass is identical to what was assumed by the experiments in the measurement). Within `HiggsSignals-1.3` the normalization of the predicted signal rates can now be evaluated in two ways:

1. The predicted SM normalized signal rates are assumed to be the same at the peak position (i.e. where the measurement has been performed). This is a valid approach if the theoretical mass uncertainties are large and the SM cross sections and branching ratios do not vary drastically between the predicted and observed mass positions.

2. The normalization is re-evaluated with the SM cross sections at the peak position. This setting is recommended if theoretical mass uncertainties are zero.

In previous versions of `HiggsSignals`, only the first option was available. This setting remains to be the default setting. If the user wishes to use the second option, the flag

```
logical :: normalize_rates_to_reference_position = .True.
```

needs to be set in `usefulbits_HS.f90`.

References

[1] P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, and G. Weiglein *Eur.Phys.J.* **C74** (2014), no. 2 2711, [arXiv:1305.1933].

[2] P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, and K. E. Williams *Comput. Phys. Commun.* **181** (2010) 138–167, [arXiv:0811.4169]; P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, and K. E. Williams *Comput. Phys. Commun.* **182** (2011) 2605–2631, [arXiv:1102.1898]; P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein, and K. E. Williams arXiv:1301.2345; P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak, *et. al.* *Eur.Phys.J.* **C74** (2014), no. 3 2693, [arXiv:1311.0055].