Exploring Contur beyond its default mode: a case study

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We discuss Contur’s different modes by studying a leptophobic Top-Colour (TC) model. We use, for the first time, higher order calculations for both the signal (NLO) and the background (up to NNLO). We compare the results between the different approaches of Contur. Furthermore, we compare these results to the ones coming from a direct search.

1 Introduction

Among the many goals of the Large Hadron Collider (LHC) is to search for physics Beyond the Standard Model (BSM). However, in its first two runs, no clear signals of New Physics were seen. Nevertheless, hundreds of measurements were published. Thus, an interesting approach would be to use these already existing measurements to test at what significance the new theoretical ideas are already excluded. A toolkit that was designed to exactly do this is the Constraints On New Theories Using Rivet (Contur) toolkit. The idea behind Contur is that BSM models implemented in Monte Carlo event generators can be compared to cross section fiducial measurements at particle level in a model independent way. It uses the hundreds of measurements already included in the Rivet (Robust Independent Validation of Experiment and Theory) repository to constraint the phase space of the BSM model.

2 Different modes of Contur

The default mode of Contur is used to look for striking deviations from the Standard Model (SM). In this scenario, Contur sets the SM background to the data. It then adds the signal to the data and checks whether there is a room for the BSM signal within the uncertainties of the data. The second, more complete approach, that can be performed by Contur is when the SM model predictions for the measurements that we are interested in are included. In this case, the SM background is set to be equal to the SM predictions. Contur then adds the signal on top of the SM theory prediction and compares the result to the data within uncertainties. Finally, Contur can also be used in the so-called “expected limit” mode. Here, the central value of the measurement is shifted to lie exactly on the simulated SM prediction while keeping the

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uncertainties of the measurement. The exclusion limits are then evaluated in the same way as in the previous case.

3 Signal and background calculation

In this case study, the signal comes from a leptophobic TC model. This model has an additional SU(3) symmetry under which only the third generation transforms. The first and second generations then transform under the original SU(3) symmetry. To prevent the bottom quark from being as massive as the top, an additional U(1) symmetry associated with a Z’ boson is considered. The two SU(3)s and U(1)s are then broken down to the SU(3)C and U(1)Y of the SM, respectively. As suggested by the name of the model, the Z’ does not couple to leptons. Furthermore, it does not couple to the second generation quarks. The two input parameter of this TC model are the mass of Z’ (M_{Z'}) and the ratio of the two U(1) coupling constants (cot \theta_H). However, using the decay width of the Z’ boson (\Gamma_{Z'}), one can work with \Gamma_{Z'}/M_{Z'} instead of cot \theta_H. We perform two calculations of the signal, one with Herwig at LO including all the two to two processes, with the Z’ boson either in the s-channel or as an external outgoing leg, and one with the PBZpWp package at NLO only considering the Z’ to t\bar{t} final state.

The partonic t\bar{t} cross section at NLO accuracy reads:

$$\sigma_{ab}(\mu_r) = \sigma_{1;1}(\alpha_S \alpha) + \sigma_{2;0}(\alpha_S^2) + \sigma_{0;2}(\alpha^2) + \sigma_{3;0}(\alpha_S^3) + \sigma_{2;1}(\alpha_S^2 \alpha) + \sigma_{1;2}(\alpha_S \alpha^2) + \sigma_{0;3}(\alpha^3)$$

The indices a and b represent the power in \alpha_S and \alpha_{\text{EW}}, respectively. For our analysis, we simulate the SM QCD t\bar{t} background (\sigma_{2;0}) and the NLO QCD correction to it (\sigma_{3;0}) using the Herwig package. We also calculate the electroweak (EW) SM t\bar{t} production (\sigma_{0;2}), the NLO QCD correction to it (\sigma_{1;2}), and the interference between QCD and EW SM top-pair production (\sigma_{1;1}) using PBZpWp. Furthermore, we include, only at 13 TeV, a sample of QCD corrections to \sigma_{2;0} up to NNLO accuracy obtained with the dijetMinNLO package. Finally, using the dijet package, we simulate the ATLAS inclusive jet and dijet cross section measurement at NLO accuracy.

4 Results

Starting with the default mode of Contur, we show in Figure 1 results using the data as background in the the M_{Z'} versus the cot \theta_H plane. While we use PBZpWp to calculate the signal at NLO in Figure 1a, in Figure 1b we use Herwig to simulate it inclusively at LO. The strongest sensitivity in both cases come from the various top measurements at low masses, the ATLAS fully hadronic measurements for masses between 2 and 3 TeV, and the jet measurements at high masses. It is visible that stronger limits are obtained in the Herwig case. This is due to the fact that at LO, not only the t\bar{t} final state is included, but also the u\bar{u} and d\bar{d} final states.

In Figure 2 we only use the PBZpWp signal and we vary the background. This is performed in the M_{Z'} versus \Gamma_{Z'}/M_{Z'} plane. The limits in Figure 2 (top left), where the background is set to the data only for measurements where we have simulated predictions, are similar but slightly weaker than in Figure 2 (top right), where the background is simulated at NLO accuracy. This is due to the fact that the SM predictions agree reasonably with the data, but overshoot it in some regions of the phase space. Furthermore, in Figure 2 (bottom left), where the background is set to be equal to the NNLO predictions where available and to NLO elsewhere, the limits are slightly stronger than the ones in the top right panel of Figure 2. The reason is that at NNLO the scale uncertainties are reduced. Finally, in the bottom right part of Figure 2, we show the expected limits using the NNLO and NLO theory predictions.

The numerical results of Figure 2 are summarised in Table 1 together with the most stringent limits coming from a direct resonance search. As explained above, we see that the limits are stronger with increasing precision. We also see that with Contur one can explore areas of the
Figure 1 – Exclusion limits for the leptophobic TC model in the $M_{Z'}$ versus the cot $\theta_H$ plane. The colored blocks in the legend show the breakdown into the most sensitive analysis pool for each scan point. The 95% CL (solid red) and 68% CL exclusion (dashed red) contours are superimposed, using the default mode of Contur (background = data). (a): the $t\bar{t}$ signal is obtained at NLO accuracy using the PBZpWp POWHEG package. (b): the signal is obtained using Herwig (inclusive LO).

Table 1 – Exclusion limits on $M_{Z'}$ obtained in this analysis. The last column shows the most stringent limits coming from a direct CMS search.

| $\Gamma_{Z'}/M_{Z'}$ [%] | Data as bgd. | NLO as bgd. | NNLO as bgd. | CMS |
|-------------------------|--------------|--------------|--------------|-----|
| 1                       | 2.29         | 2.35         | 2.50         | 3.80|
| 10                      | 3.17         | 3.22         | 3.55         | 5.25|
| 30                      | 4.01         | 4.04         | 4.53         | 6.65|
| 50                      | 4.54         | 4.61         | 5.19         | -   |

Summary

We performed an analysis using the different modes of Contur. We validated the previous approach employed with Contur (Data = SM) and used, for the first time, higher order calculations for both the signal (NLO) and the background (up to NNLO). This analysis shed light on both the pros and cons of a Contur like approach. A wide range of BSM models can be rapidly checked using this toolkit and exclusion limits can be derived in regions of the parameter space that were not studied before. In the TC model case, the direct searches were more efficient than our analysis. However, for models with more free parameters and more complex phenomenology, or even for unexplored models, the Contur approach is expected to be much more competitive.
Figure 2 – Same as Figure 1, but in the $M_{Z'}$ versus $\Gamma_{Z'}/M_{Z'}$ plane, for $Z' \rightarrow t\bar{t}$ (PBZpWp). Top left: default mode, but only using measurements where SM predictions are available. Top right: background = NLO SM predictions. Bottom left: background = NNLO SM predictions where available, and NLO elsewhere. Bottom right: expected limit using NNLO predictions.

Acknowledgments

This work was supported by the National Science Centre, Poland, under research grant 2017/26/E/ST2/00135, the BMBF under 05H18PMCC1, the IN2P3 project “Théorie – BSMG”, and the European Union’s Horizon 2020 research and innovation programme as part of the Marie Skłodowska-Curie Innovative Training Network MCnetITN3 (grant agreement no. 722104).

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ATLAS Hadronic $t\bar{t}$

CMS Hadronic $t\bar{t}$

ATLAS $E_T^{miss} + jet$

ATLAS $\ell + E_T^{miss} + jet$

ATLAS jets

CMS $\ell + E_T^{miss} + jet$

ATLAS $\mu\mu + jet$

CMS $\ell + E_T^{miss} + jet$

ATLAS $e\mu + jet$

ATLAS $e\ell_1 + E_T^{miss} + jet$