1. Irreducible backgrounds and measurement uncertainties [1] , [2] , [3]

1.1 Introduction

The general principle of minimising the model-dependence of results from particle colliders by making measurements of well-defined final states in fiducial regions is by now widely accepted, and implemented by the LHC collaborations. The fiducial regions are designed to reflect the acceptance of the detectors and data-selection. The final states are defined in terms of stable, or quasi-stable, particles. Increasingly impressive theoretical calculations are able to implement the appropriate kinematic cuts, and modulo some uncertainty associated with soft physics (for example hadronisation), can predict precisely what is actually being measured, without the need for additional assumptions or extrapolations into unmeasured regions of phase space.

This represents great progress. One area, however, where the principle of defining a measurement in terms of the final state is not so widely implemented, is in the consideration of background processes and their subtraction. Often backgrounds are subtracted using a mixture of theoretical and data-driven techniques, even though in some cases the backgrounds are strictly speaking "irreducible", in that they produce final states identical to the "signal" final state (even in a perfect detector) and thus should be added to the signal at the amplitude, rather than cross-section, level. These subtractions are also often carried out before, or intermingled with, the unfolding and correction for detector effects such as efficiency and resolution, and thus are impossible to revert or reproduce once applied.

In practice, the uncertainty introduced by such subtractions is often insignificant compared to other uncertainties in the measurements, for example because the kinematic overlap is in fact small and interference terms are negligible. Nevertheless, as precision of both experiment and theory increase, such considerations can become important in some processes. In this contribution we highlight some such cases in an attempt to raise awareness of the issues for future studies.

1.2 Single top and $W + b$-jet production

An example of a final state in which two contributions are often treated as distinct processes is the measurement of a leptonically-decaying W boson (that is, charged lepton plus missing transverse energy) in association with a b-tagged hadronic jet. The publication of the ATLAS analysis of 7 TeV LHC collision data [1] contains a measurement of the fiducial $W + b$-jet cross section, presented as a function of jet multiplicity and of the transverse momentum of the leading b-jet. The $W + b$-jet cross-section, corrected for all known detector effects, is quoted in a limited kinematic range, using jets reconstructed with the anti-kt clustering algorithm with transverse momentum above 25 GeV and absolute rapidity within 2.1. The measurement is presented before and after the subtraction of the single-top contribution to the identical final state. Both versions are available in HEPDATA [2] and Rivet [3][4]. The unsubtracted version is shown in Fig. 1, and the subtracted version in Fig. 2, in the case where the b-jet is the only jet in the ducial region (1-jet bin) and when there is an additional jet (2-jet bin).

Several things may be noted:

- In neither case does the theory describe the data especially well. This is a challenging final state to predict and the theory is likely to be superseded by more sophisticated and accurate predictions in future (indeed, NLO implementations of this process in MC are already available, as discussed in Section **??** of these proceedings). This strongly mitigates against embedding in a dependency on

[1]Section coordinators: Jonathan M. Butterworth, Frank Krauss

[2]Vitaliano Ciulli, Paolo Francavilla, Vasilis Konstantinides, Piergiulio Lenzi, Carlo Pandini, Luca Perrozzi, Lorenzo Russo, Marek Schoenherr, Umit Utku, Lorenzo Viliani, Ben Waugh

[3]VC and LR acknowledge support by MIUR Italy under Grant Agreement 2012Z23ERZ of PRIN 2012

[4]The Rivet analysis was modified to add the histograms for the unsubtracted data.

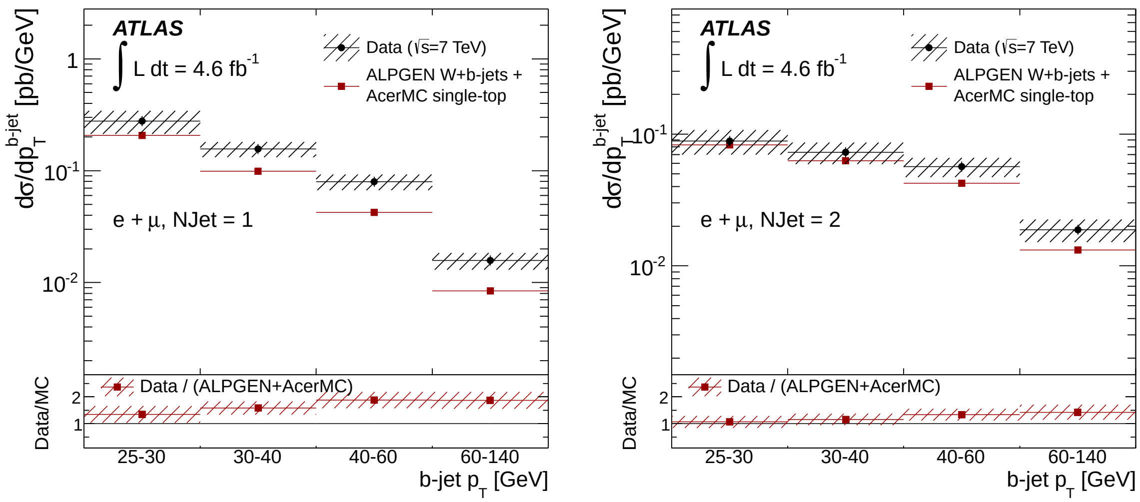

Fig. 1: Measured differential $W + b$-jet cross-section before single-top subtraction as a function of the transverse momentum of the b-jet, in the 1-jet bin (left) and 2-jet bin (right). The measurements are compared to the sum of separate $W + b$-jet and single-top predictions obtained using ALPGEN interfaced to HERWIG and JIMMY and scaled by a NNLO inclusive W normalization factor, and ACERMC interfaced to PYTHIA and scaled to a NLO single-top cross-section. The ratios between measured and predicted cross-sections are also shown. From [1].

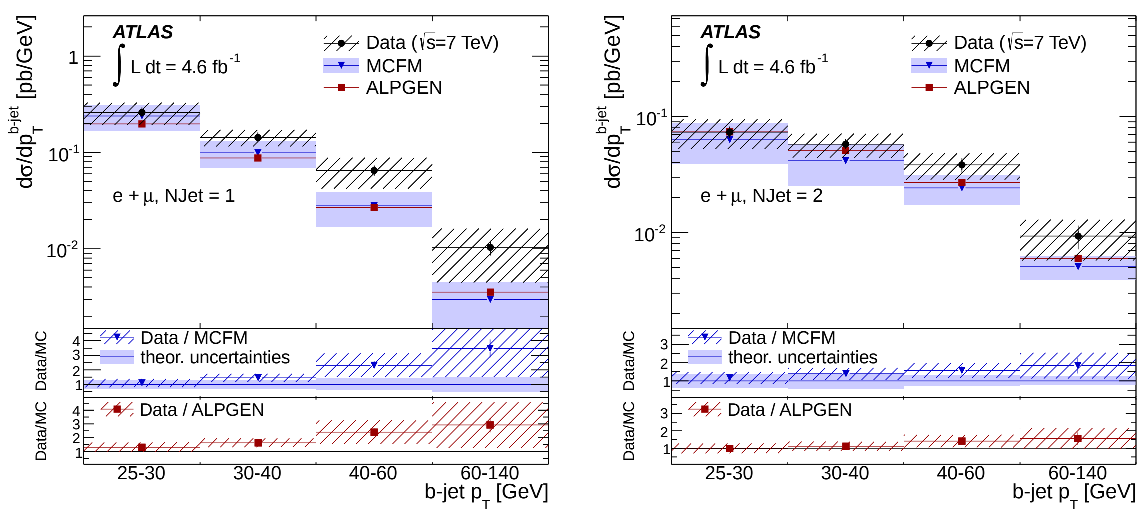

Fig. 2: Measured differential $W + b$-jet cross-section after single-top subtraction as a function of the transverse momentum of the b-jet, in the 1-jet bin (left) and 2-jet bin (right). The measurements are compared to the a calculation of $W + b$-jet production in the absence of top quark propagators obtained using ALPGEN interfaced to HERWIG and JIMMY and scaled by a NNLO inclusive W normalization factor, and ACERMC interfaced to PYTHIA and scaled to a NLO single-top cross-section. The ratios between measured and predicted cross-sections are also shown. From [1].

the theory in the experimental analysis - as is the case if the background is subtracted at detector-level - and is a strong motivation for the unsubtracted version of the measurement.

- The contributions from diagrams with and without top are comparable (as can be noted from the cross section in the highest p_T bin).
- The data uncertainties on the unsubtracted version are smaller.

Integrated over p_T, the unsubstracted fiducial cross section is $9.6 \pm 0.2(stat) \pm 1.7(syst)$ pb, a relative systematic uncertainty of 18%. The corresponding subtracted measurement is $7.1 \pm 0.5(stat) \pm 1.4(syst)$ pb, a relative systematic uncertainty of 20% - a small but noticeable decrease in precision. Looking in more detail, the main contributions to the systematic errors are:

- Jet energy scale: 10-50%
- Modelling of initial and final state QCD radiation (Wb, single top, $t\bar{t}$): 2-30%
- b-tagging: 1-8%
- MC modelling of the Wb process: 2-8%

The fact that jet energy scale dominates masks, to a large extent, the effect of the modelling uncertainties introduced by the background subtraction. The uncertainty due to the modelling of QCD radiation varies strongly with jet p_T. This is exactly the kind of model dependence which one would expect to increase if a theory-based background subtraction is made, and indeed, in the highest p_T bin the systematic uncertainty goes from 16% before subtraction to 54% after it (compare Table 4 with Table 9 of Ref. [1]).

The comparisons were repeated using Sherpa 2.2 [4] and Herwig7 [5].
For Sherpa, all intermediate particles in the matrix element are kept on-shell and the AMEGIC ME generator is used for LO calculations [6]. Only decays of the W boson to the electron channel are allowed. Multi-parton interactions are switched off. The Sherpa default 5-flavour pdf library (NNPDF [7]) is used. In Wb production without tops, the b-quark is treated as massive with a mass of 4.75 GeV and the W boson is treated through the narrow width approximation. The order of the electroweak couplings is fixed to 2. For single top production, the b-quark is treated as massless in the matrix element calculation but retains its mass settings in the rest of the simulation. QCD and EW order couplings are not fixed. Production modes include all channels: s-channel, t-channel and tW single-top channels.
For Herwig, the built-in matrix elements for W+jet and single top were used. All leptonic decays were generated, but the electron only channel was selected in Rivet, with a normalisation factor of three applied post-hoc. Production includes s-channel, t-channel and tW single-top channels. The pdf MMHT2014 LO [8] is used.

The comparison of the non-top diagrams only to the subtracted data is shown in Fig 3. With these settings, Herwig agrees with the data normalisation both in the 1-jet and 2-jet bins. It correctly models the shape of the b-jet p_T in the 1-jet bin, but fails to describe it in the 2-jet bin. Sherpa models well the p_T dependence in both jet bins, but overestimates the normalisation of the 1-jet bin by nearly a factor of 2.

In Fig. 4 the unsubtracted measurement is shown, compared to Herwig and Sherpa. The predicted distributions from $W + b$-jet diagrams are shown without and with top contribution (in the latter case the interference terms are neglected). Once more, Herwig agrees quite well with the data normalisation, and models well the b-jet p_T distribution in the 1-jet bin, while struggling with this dependences in the 2-jet bin. Also in this case Sherpa overestimates the normalisation of the 1-jet bin (this time by about 65%), but correctly models the normalisation of the 2-jet bin and the p_T dependence in both jet bins, within the data uncertainties.

In Fig. 5 we show the MC predictions for 13 TeV collisions. These measurements have yet to be performed, but the main point to be made here is that the total top contribution rises from 15% (32%) to 23% (42%) according to Sherpa (Herwig), with greater effects in some regions. This shows that any problems and uncertainties associated with the subtraction of irreducible backgrounds are likely to become more severe at higher energies. The differences between the generators themselves is another indication of

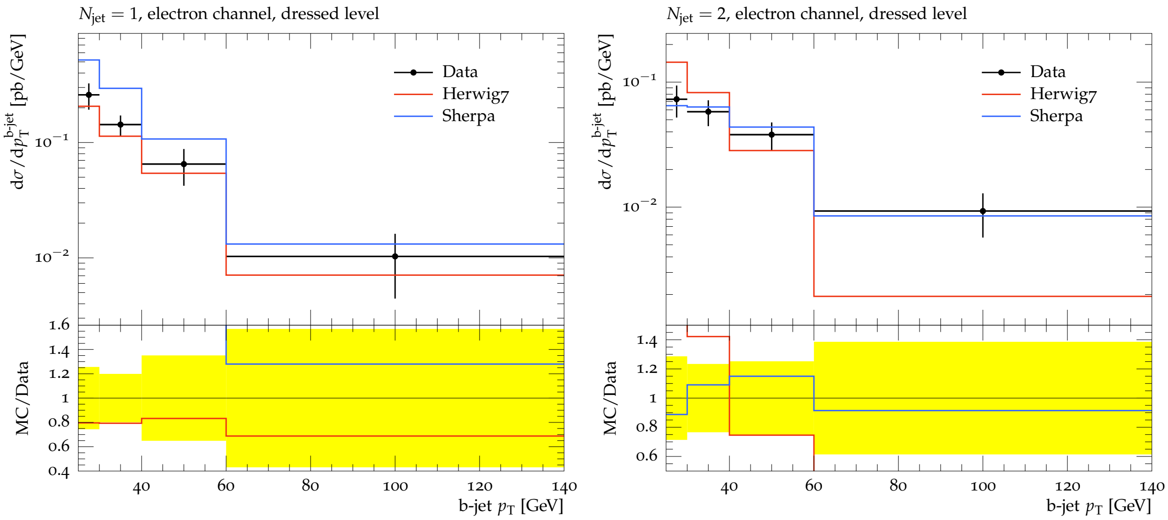

Fig. 3: Measured differential $W + b$-jet cross-section after single-top subtraction as a function of the transverse momentum of the b-jet, in the 1-jet bin (left) and 2-jet bin (right). The measurements are compared to the expectations of Sherpa and Herwig, for Wb production processes excluding diagrams containing top quarks.

the challenges associated with predicting these cross sections, and thus the need to minimise the theory dependence of the measurement.

1.3 Diboson plus jet production

Processes in which two W-bosons and two jets (including possibly b-jets) are produced are of great interest at the LHC. Contributing amplitudes include:

- $t\bar{t}$ (with on- or off-shell top quarks),
- genuine QCD processes with b quarks already entering from the initial state or being pair-produced in the final state through gluon splitting amplitudes,

and, to a lesser extent,

- electroweak processes such as vector-boson fusion diagrams including the Higgs boson as a propagator and b-associated Higgs boson production.

In Sherpa, the leading order processes for $t\bar{t}$ and tWb (both with on-shell tops), and $WWb\bar{b}$ (excluding all top contributions) were generated separately, and the full leading order $WWb\bar{b}$ process, including all top contributions was also generated for comparison. All processes were generated for centre-of-mass energies of 13 TeV.

An initial set of basic selection cut was applied, requiring two isolated leptons with $|\eta| < 2.5, p_T >$ 25 GeV and missing $E_T > 25$ GeV, typical of an experimental analysis. The multiplicity of jets (identified with the anti-k_T algorithm, $R = 0.4$, $p_T > 25$ GeV, $|\eta| < 4.5$) in events passing these cuts is shown in Fig. 6. It can be seen that the diagrams involving at least one top quark dominate, though the contribution of non-top diagrams is significant at low jet multiplicities. Fig. 6 also compares the incoherent sum of the different contributions with the coherently generated $WWb\bar{b}$ process. It can be seen that the interference terms are largely positive.

Further cuts were applied to mimic a vector-boson-fusion like analysis, requiring that there are at least two jets in opposite hemispheres of rapidity, with a rapidity difference between them $\Delta y_{jj} > 2.4$ and a dijet invariant mass $m_{jj} > 500$ GeV, and after additional cuts on the transverse mass of the dilepton $m_{\ell\ell} > 20$ GeV and missing $E_T > 40$ GeV. Fig. 7 shows that the same general features persist, with the interference terms being large and positive for jet multiplicities below five.

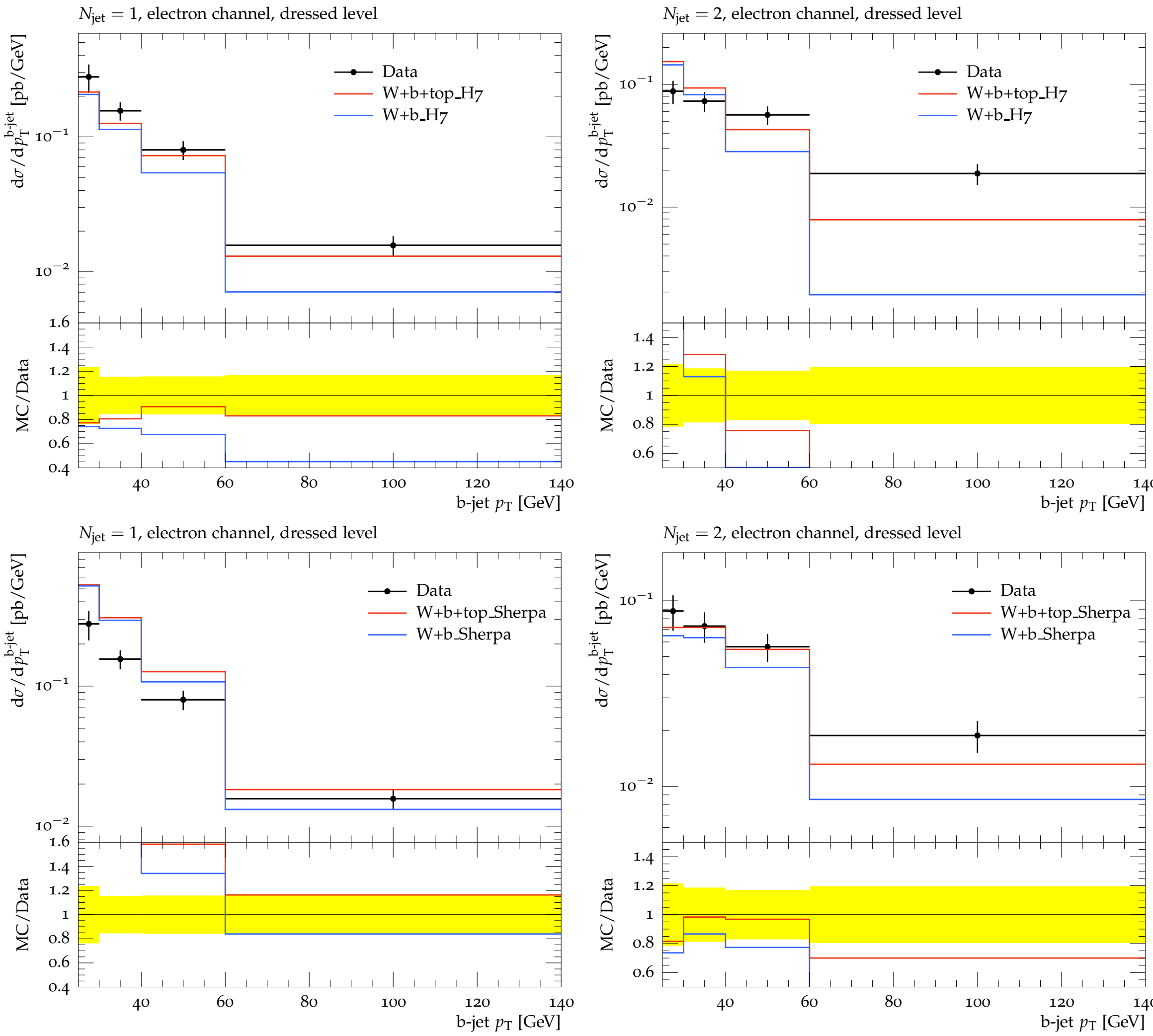

Fig. 4: Measured differential $W + b$-jet cross-section, including single-top contributions, as a function of the transverse momentum of the b-jet, in the 1-jet bin (left) and 2-jet bin (right). The measurements are compared to the Sherpa (top) and Herwig (bottom) calculations of $W + b$-jet production including resonant top contributions, but excluding finite width effects and interference terms between top and non-top diagrams. The contribution from non-top diagrams alone is also shown.

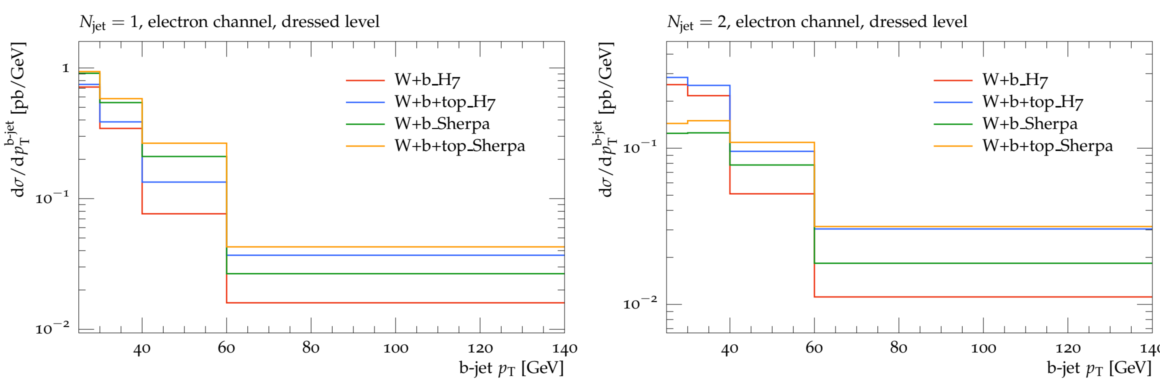

Fig. 5: Differential $W + b$-jet cross-section at 13 TeV as a function of the transverse momentum of the b-jet, in the 1-jet bin (left) and 2-jet bin (right). In both Sherpa and Herwig calculations of $W + b$-jet production including resonant top contributions, finite width effects and interference terms between top and non-top diagrams are not taken into account. The contributions from non-top diagrams alone are also shown.

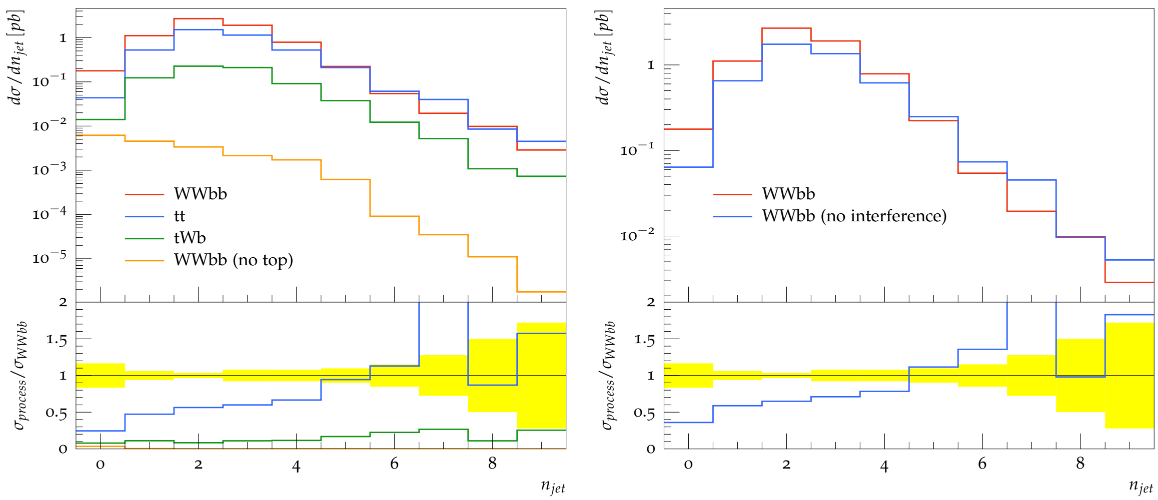

Fig. 6: Simulated $WWb\bar{b}$ events at 13 TeV using Sherpa. Individual contributions (left) and the comparison between incoherent and coherent sums (right) are shown.

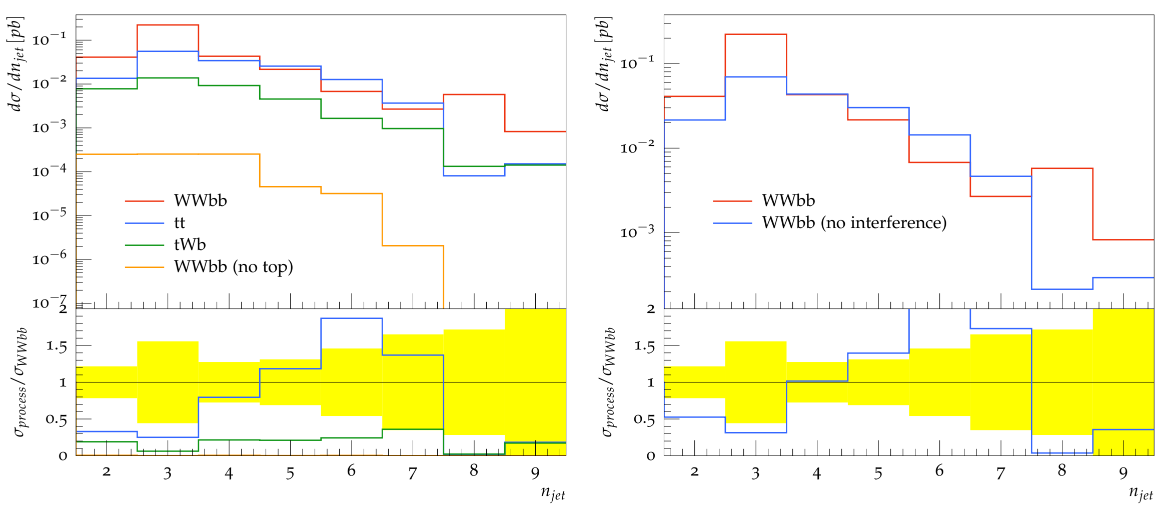

Fig. 7: Simulated $WWb\bar{b}$ events at 13 TeV using Sherpa, after vector-boson-fusion selection cuts. Individual contributions (left) and the comparison between incoherent and coherent sums (right) are shown.

1.4 Conclusions

This brief study exploits the Wb measurement made by ATLAS at 7 TeV, and the multi-process capabilities of Sherpa, to illustrate how distinct processes and their interference contribute to the same measurable $W + b$-jet final state. The discussion draws the attention on the subtraction of irreducible backgrounds which, although commonly used, can increase the model-dependence of systematic uncertainties and lead to unphysical results, since the interference terms are not treated correctly. The ATLAS measurement shows increased systematic uncertainties in the region of high b-jet p_T when single top background contributions are subtracted. The simulation shows that the background will become more significant at 13 TeV, therefore expecting further increase of uncertainties. Furthermore, the studies performed with Sherpa indicate that, even after realistic selection of vector-boson-fusion-like topologies, interference terms are significant in $WWbb$ production. In conclusion, a careful treatment of the irreducible background in future measurements at the LHC will become more and more relevant when presenting the results.

References

[1] G. Aad *et. al.*,, **ATLAS** Collaboration *JHEP* **06** (2013) 084, [`1302.2929`].

[2] “HEPDATA, IPPP http://hepdata.cedar.ac.uk.”

[3] A. Buckley, J. Butterworth, L. Lonnblad, D. Grellscheid, H. Hoeth, *et. al.*, *Comput.Phys.Commun.* **184** (2013) 2803–2819, [`1003.0694`].

[4] T. Gleisberg, S. Hoeche, F. Krauss, M. Schonherr, S. Schumann, F. Siegert, and J. Winter, *JHEP* **02** (2009) 007, [`0811.4622`].

[5] J. Bellm *et. al.*, `1512.01178`.

[6] F. Krauss, R. Kuhn, and G. Soff, *JHEP* **02** (2002) 044, [`hep-ph/0109036`].

[7] R. D. Ball *et. al.*,, **NNPDF** Collaboration *JHEP* **04** (2015) 040, [`1410.8849`].

[8] L. A. Harland-Lang, A. D. Martin, P. Motylinski, and R. S. Thorne, *Eur. Phys. J.* **C75** (2015), no. 5 204, [`1412.3989`].