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

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 design 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 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 undo or redo after the fact.

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, in some processes, and as precision of both experiment and theory increase, such considerations can become important. 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 $W + b$ 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 collision data[1] contains a measurement of the fiducial $W + b$-jet cross section both with and without the subtraction of the single-top contribution to the identical final state. Both versions are available in HEPDATA [2] and Rivet [3][3]. The unsubtracted version is show in Fig. 1, and the subtracted version in Fig. 2.

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. This strongly mitigates against embedding in a dependency on 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 (compare the cross section in the highest p_T bin, for example).
- 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 fractional systematic uncertainty of 18%. The corresponding subtracted measurement is $7.1 \pm 0.5(stat) \pm 1.4(syst)$ pb, a fractional systematic uncertainty of 20% - a small but noticeable effect decrease in precision. Looking in more detail, the main contributions to the systematic errors are

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

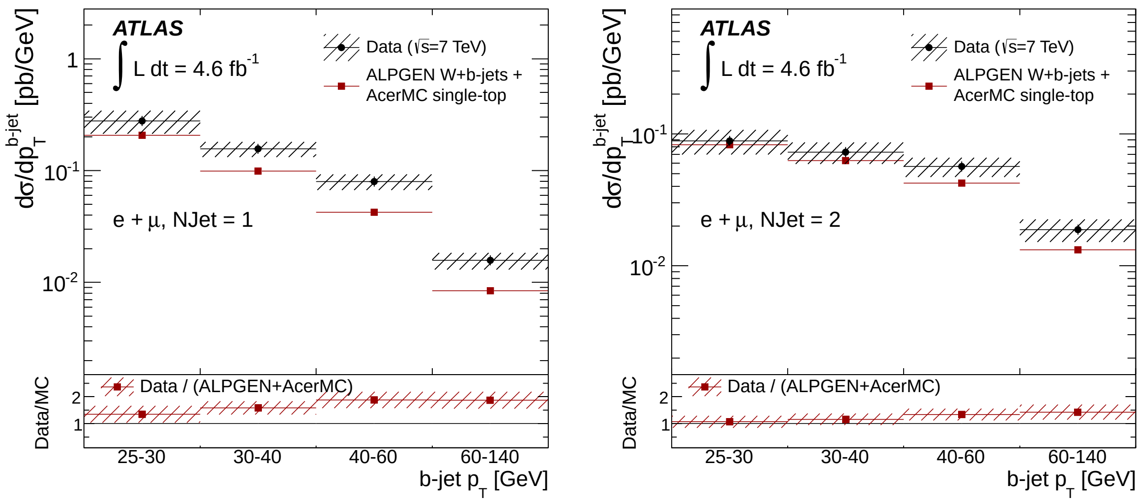

Fig. 1: Measured differential $W + b$-jets cross-section without single-top subtraction as a function of the transverse momentum of the b-jet, in the case where the b-jet is the only jet in the fiducial region (left) or when there is an additional jet (right). The measurements are compared to the sum of seperate $W + b$-jets 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].

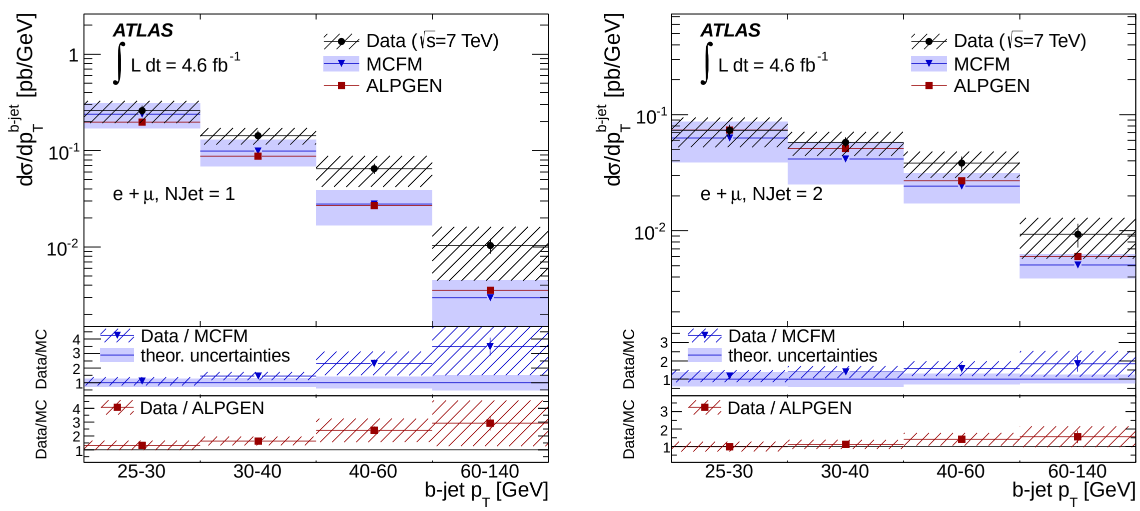

Fig. 2: Measured differential $W + b$-jets cross-section after single-top subtraction as a function of the transverse momentum of the b-jet, in the case where the b-jet is the only jet in the fiducial region (left) or when there is an additional jet (right). The measurements are compared to the a calculation 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].

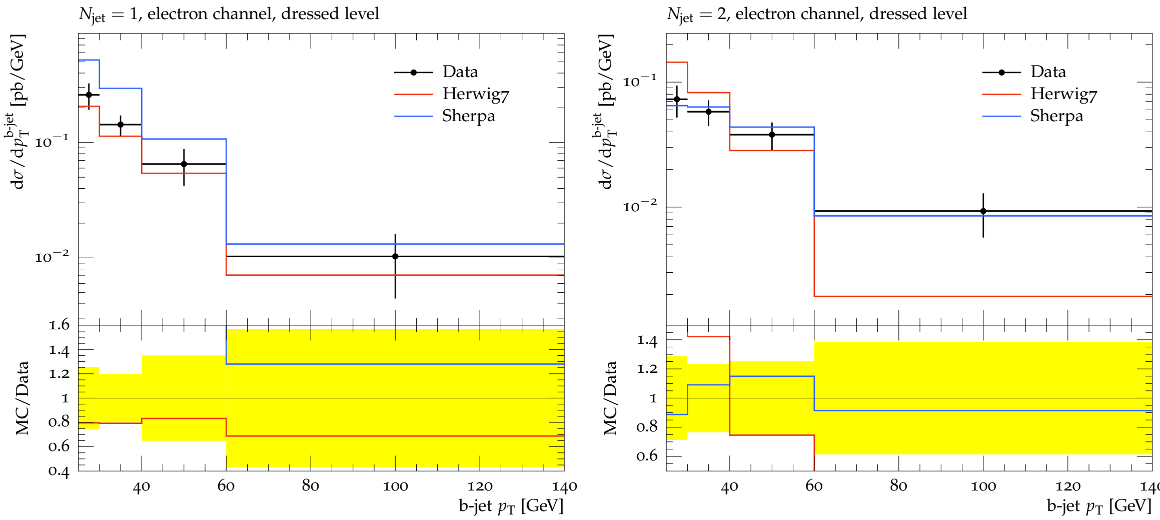

Fig. 3: Measured differential $W + b$-jets cross-section after single-top subtraction as a function of the transverse momentum of the b-jet, in the case where the b-jet is the only jet in the fiducial region (left) or when there is an additional jet (right). The measurements are compared to the expectations of Sherpa and Herwig, for Wb production processes excluding diagrams containing top quarks.

- Jet energy scale: 10-50%
- Modelling of initial and final state QCD radiation on these two processes and on $t\bar{t}$: 2-30%
- b-tagging 1-8%
- MC modelling (but only of the Wb signal) 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 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 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. (what PDF?)

The comparison of the non-top diagrams only to the subtracted data is shown in Fig 3. With these settings, Herwig gets the normalisation correct, agrees with the data normalisation and with the shape of the 1-(b)-jet contribution, but fails to describe the p_T dependence of the 2-jet contribution. Sherpa models the p_T dependence of both contributions well, but overshoots the normalisation of the 1-jet contribution by nearly a factor of 2.

In Figs 4 the unsubtracted measurement is shown, compared to first Herwig and Sherpa. The contribution from non-top diagrams is shown again, as well as sum of this and the single top contributions

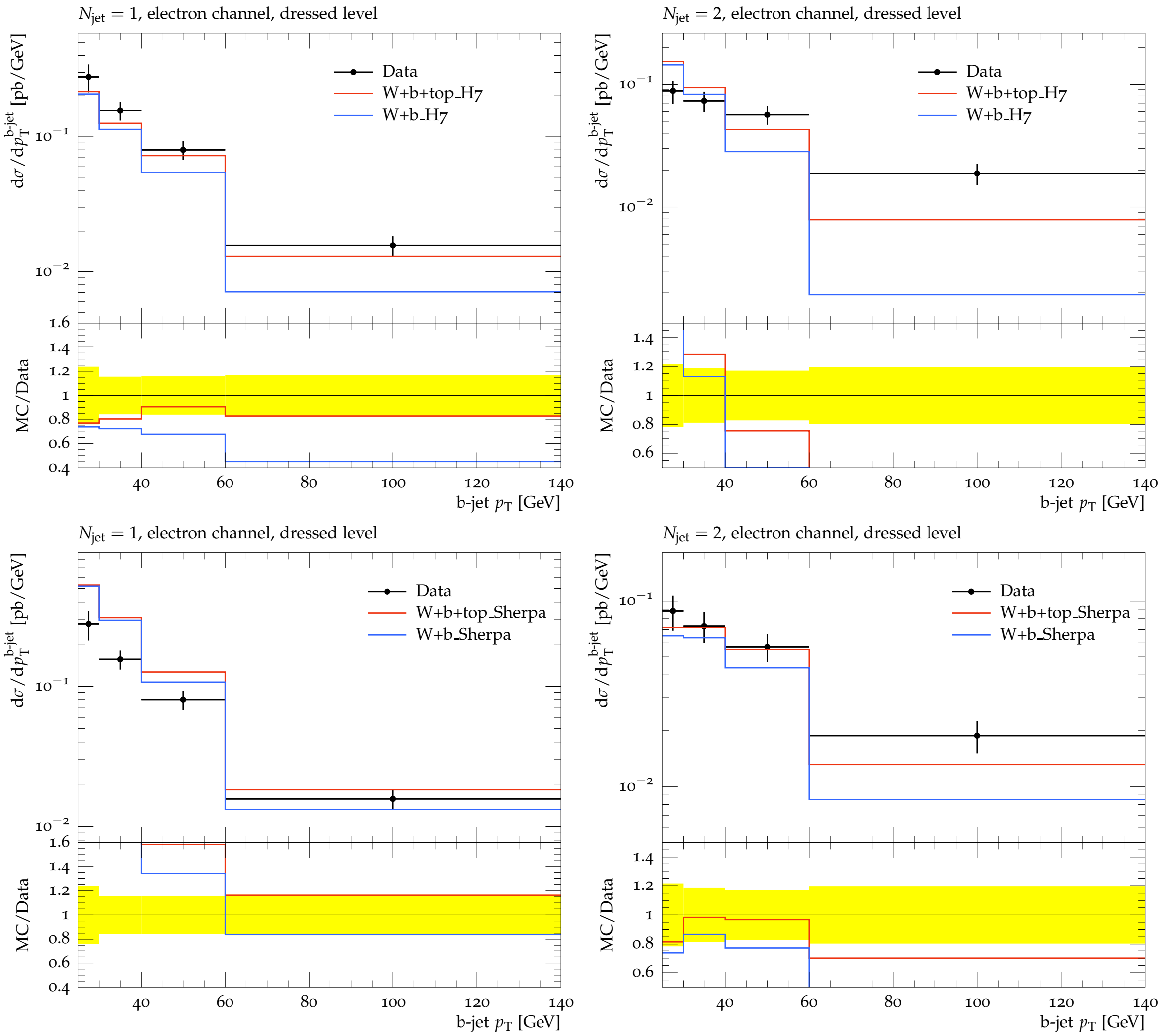

Fig. 4: Measured differential $W + b$-jets cross-section, including single-top contributions, as a function of the transverse momentum of the b-jet, in the case where the b-jet is the only jet in the fiducial region (left) or when there is an additional jet (right). The measurements are compared to the Sherpa and Herwig 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.

expected by the generator (Interference terms are neglected). Herwig again gets the normalisation about right, and models the p_T distribution of the 1-jet distribution well, while struggling with this dependences for the 2-jet distribution. Sherpa still overshoots normalisation of the 1-jet contribution (this time by about 65%), but models the normalisation of the 2-jet contribution, and the pT dependence of both contributions, reasonably well 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 the challenges associated with predicting these cross sections, and thus the need to minimise the theory dependence of the measurement.

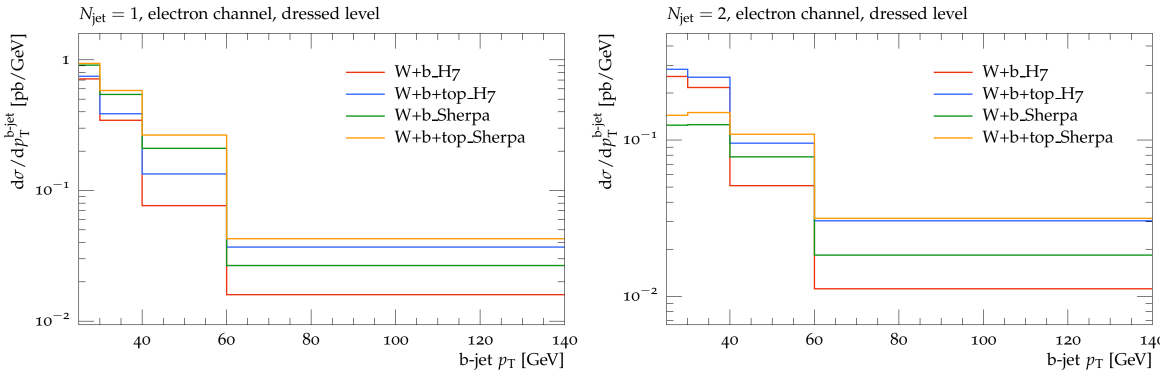

Fig. 5: Differential $W + b$-jets cross-section at 13 TeV as a function of the transverse momentum of the b-jet, in the case where the b-jet is the only jet in the fiducial region (left) or when there is an additional jet (right). In both Sherpa and Herwig calculations of $W + b$-jet production including 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.

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 were 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. 6a. 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. 6b 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 and with a rapidity difference between them $\Delta y_{jj} > 2.4$, and having 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 mulitiplicities below five.

1.4 Conclusions

This brief study exploits a measurement made by ATLAS, and the multi-process capabilities of Sherpa, to illustrate the fact that many apparently distinct processes may contribute to the same measurable final state. The treatement of the these processes by the experiments is important. Subtraction of irreducible backgrounds can increase the model-dependence of systematic uncertainties, and is unphysical, in the sense that interference terms are not treated correctly. In this discussion, both these effects are observed. The 7 TeV Wb measurement by ATLAS shows increased systematic uncertainties in the region

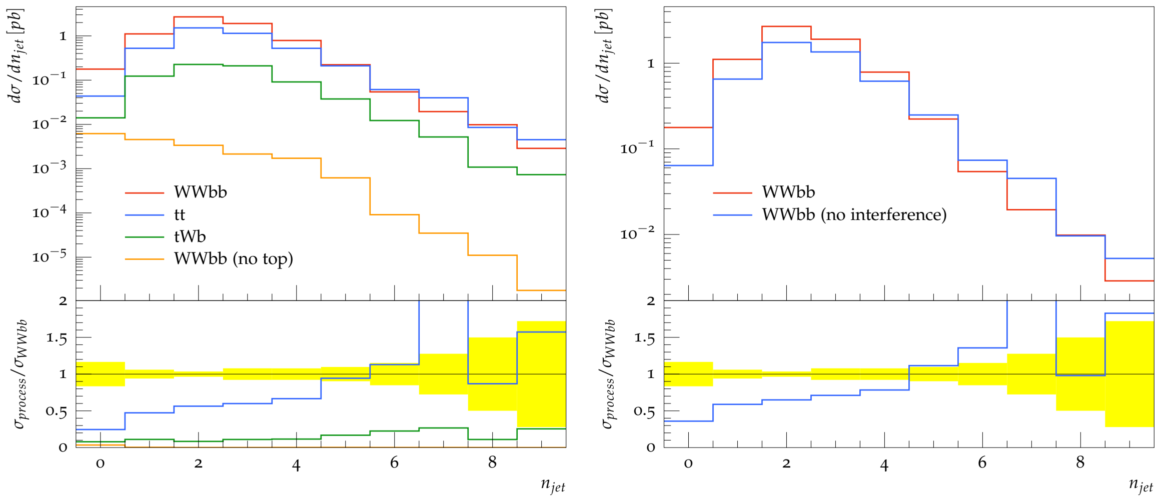

Fig. 6: 13 TeV $WWb\bar{b}$ events simulated using Sherpa. (left) individual contributions (right) comparison between incoherent and coherent sums.

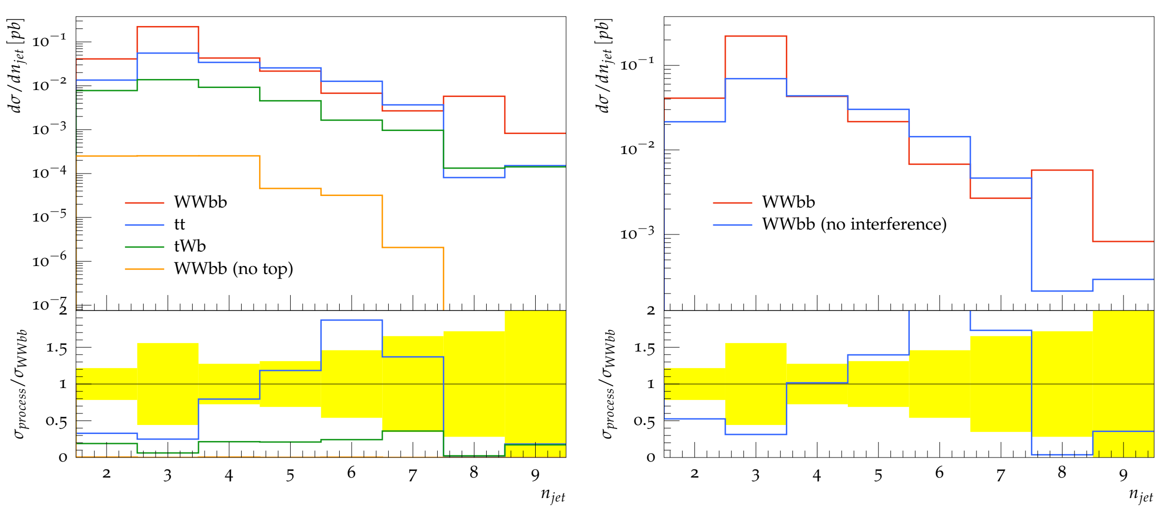

Fig. 7: 13 TeV $WWb\bar{b}$ events simulated using Sherpa, after vector-boson-fusion selection cuts. (left) individual contributions (right) comparison between incoherent and coherent sums.

of high jet-p_T if top contributions are subtracted. These contributions will become more significant at 13 TeV, and so the problem can be expected to become worse. And Sherpa studies indicate that, even after realistic selection of vector-boson-fusion-like toplogies, interference terms are signficant in $WWbb$ production. In conclusion, the treatment of irreducible background in future measurements at the LHC merits more careful attention.

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