# Bringing b-jet distributions observed in data to a comparison with NLO perturbative QCD predictions

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The selection of events with a Z boson and b-jets can easily be defined on an purely experimental ground by defining the physics objects in the final states (two leptons of opposite charge with invariant mass close to the Z mass, low missing transverse energy and one, ore more, jets identified as containing b-hadrons) through the signatures each of them leave in the ATLAS detector. However, the comparison with theory predictions, which come from scattering amplitudes with partons in the initial and final state, require a very careful matching of the definition of the involved physics objects, not only in terms of the kinematic acceptance cuts, but also of their intrinsic definition. A few studies developed for a consistent comparison of the differential production cross section of b-jets produced in association to a Z boson, in the extension of the measurement in [1], with predictions by the MCFM [2] program are discussed here.

The signal is defined at the particle level, matching as closely as possible the detector level selection, to minimise the introduction of theoretical model-dependent corrections. For the signal leptons, either "born" (the leptons directly from the $Z$ boson decay), "bare" (the final state leptons, i.e. after FSR) or "dressed" leptons (final state leptons are dressed with final state photons lying within a cone of $\Delta R < 0.1$) can be used. For particle-level jets, the set of particles passed to the jet-finder needs to be defined. The determination of jet flavour uses the flavour of the hadrons contained within them.

- "dressed" leptons are considered: all photons in a R $< 0.1$ cone around any muon or electron are added to that electron or muon.
- any leptons with $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.5$ are then considered. An opposite charge pair with a dilepton mass $76 < M < 106$ GeV are taken as the signal leptons.
- all other particles are passed to the jet finder (including any muons and neutrinos), and the anti-$k_t$ algorithm with a distance parameter of 0.4 is used to reconstruct jets.
- jets with $p_{\mathrm{T}} > 20$ GeV and $|y| < 2.4$ are considered. Any jets within $\Delta R < 0.5$ of a signal lepton are discarded.
- heavy flavour matching is done at the particle level. Any weakly-decaying B hadron with $p_{\mathrm{T}} >$ 5 GeV and which has no B hadron daughters is considered. Any jet which matches such a hadron (based on a simple $\Delta R < 0.3$ matching) is considered as a b-jet. If there is no B hadron, a charm hadron is searched for and the jet tagged as a c-jet if one is found. If neither are found, the jet is labelled a "light" jet.

A next-to-leading order prediction is obtained from MCFM using CTEQ10 PDFs. MCFM is a parton level pQCD calculation, with partons clustered into jets in the final state, which allows event generation for a flexible implementation of the kinematic requirements defining a fiducial signal. In this case, leptons and jets are required to have $p_{\mathrm{T}} > 20$ GeV and to be produced at $|\eta| < 2.5$ and $|y| < 2.4$, respectively. In addition the di-lepton invariant mass has to be in the range $76 - 106$ GeV. Lepton-jet overlap removal criteria are applied consistently with the particle level selection applied in data and the jets are accepted as b-tagged if they match a b-parton according to the same criteria applied to B hadrons. The MCFM Monte Carlo capability is exploited to obtain a break-down of the predicted cross section, passing the acceptance requirements, into the various intervals of the differential distributions measured in data.

In general, to obtain a full prediction, results from several sub-processes, implemented in the calculation, must be combined. In particular, for the $Z + b$ prediction at NLO the various sub-processes involved will describe final states with only one b-jet, events with two b-jets one of them not in the acceptance or merged to the other one in the jet-finding algorithm and events with b-jets in the acceptance. The renormalisation and factorisation scales in the calulation are set to the sum in quadrature of the $Z$ boson mass and $p_{\mathrm{T}}$ on an event by event basis.

The uncertainty on the prediction has three main sources: the choice of the scales used in the calculation, the uncertainty on $\alpha_s$ and input PDF set. The dependency of the results on the choice of the renormalisation and factorisation scales is assessed by independently shifting up then down the two scales by a factor of 2. The calculation is repeated by changing the value of the strong coupling constant of plus and minus one standard deviation consistently in the matrix element and in the PDF set applied. The remaining uncertainty arising from the experimental contraints on the PDF set adopted is also assessed, by applying the recommended procedures. Finally, the spread of the difference in the prediction obtained by changing the PFD sets is applied as a further systematic uncertainty.

The data measurement is obtained based on a particle-level signal definition quite close to the experimentally accessible observable and, therefore, cannot be directly compared to the parton level MCFM prediction. In particular, the parton level MCFM prediction must be corrected for the effects of QED FSR from the leptons and for the "non-perturbative corrections" induced by hadronisation, underlying event overlapping with the hard scattering and multiparton interactions.

The QED correction is derived from the Alpgen samples by comparing the results of the nominal particle level selection, based on "dressed" leptons, with those obtained using Born leptons, i.e. leptons from the Born level multi-parton Alpgen matrix element, before the radiation is applied through the interface with the Herwig parton-shower. The QED FSR correction appears to be rather stable within the phase-space of interest for the measurements described here; therefore, an average value of about 3% has been estimated and applied in all bins. The error on the correction arises from the MC statistics of the Alpgen sample.

Non-perturbative corrections are derived using `sherpa 1.4.1`, using the CT10 PDF set. In the `sherpa` multi-parton Monte Carlo both matrix element and parton shower can lead to $b$-jet production in the final state and all overlaps are internally removed. The processes contributing to the signal definition can be separated into two categories: processes with at least one hard jets with a single heavy flavour parton and processes where a gluon splits in two b-partons close in phase space which are not resolved by the jet-finding procedure. The contributions from the two categories are estimated separately and then summed up. Multipartion interactions and fragmentation are, typically, emulated, but this features can be disabled thus allowing to compare parton-level and hadron-level predictions. The non-perturbative corrections are estimated as the ratio of the yield of signal b-jet or $Z+bb$ events predicted in each analysis bin with and without the emulation of hadronisation and multi-partin interactions. In one case, b-jets are defined by a match to a $b$ quark (equivalent to MCFM) , in the other case, b-jets match a B hadron as described earlier. High statistics samples of events with two oppositely charged muons and up to four partons in the final state have been produced. The same procedure is applied using the `pythia` Monte Carlo, in order to assess the systematic uncertainly on the correction as the absolute difference between the results obtained with the two simulations. As an example, the distributions predicted by `sherpa` and `pythia` and the corresponding estimate of the non-perturbative corrections are shown in Fig. 1.

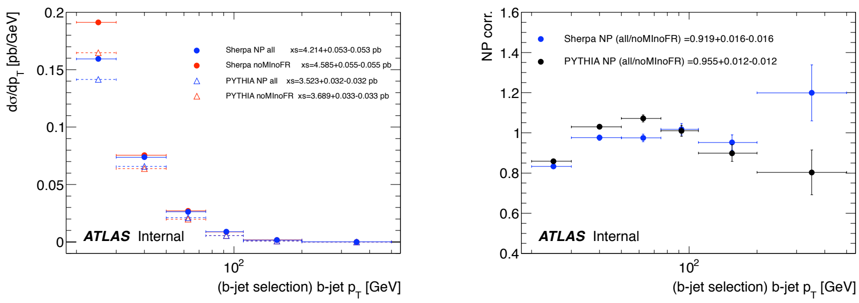


Figure 1. QCD non-perturbative corrections (NP) for the differential distributions of b-jet $p_{\rm T}$. The effects are evaluated with `sherpa` and `pythia` as the ratio of the predictions for the differential cross-sections, shown to the left, with all NP effects enabled to the predictions obtained when disabling all effects.

## REFERENCES

1. ATLAS Coll.(G. Aad et al.), Phys. Lett. B706 (2012) 295-313.
2. J. Campbell and R.K. Ellis and F. Maltoni and S. Willenbrock, Phys. Rev. D73 (2006) 054007.