Automated QCD and Electroweak Corrections with Sherpa

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Precise theoretical predictions are vital for the interpretation of Standard Model measurements and facilitate conclusive searches for New Physics phenomena at the LHC. In this contribution I highlight some of the ongoing efforts in the framework of the Sherpa event generator to provide accurate and realistic simulations of Standard Model production processes. This includes the automated evaluation of NLO QCD and NLO EW corrections and their consistent consideration in the parton-shower evolution of scattering events. Particular emphasis is given to examples and applications involving the production of top quarks.

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1 Introduction

Precise predictions for the production rates and kinematical distributions of Standard Model (SM) processes are of utmost importance for measurements of SM parameters, e.g. couplings and particle quantum numbers, and meaningful searches for New Physics phenomena. To link accurate perturbative calculations to particle-level final states in collider experiments Monte Carlo event generators prove to be indispensable. Ideally these tools should provide the highest possible perturbative accuracy for the considered hard-production process, consistently combined with a resummation of large scale logarithms and linked to phenomenological models for non-pertubative aspects, such as hadronization and underlying event [1]. This should be achieved such, that the perturbative accuracy is preserved and that related theoretical uncertainties remain quantifiable, allowing to reliably contrast experimental measurements with SM expectations.

In this short contribution I highlight some recent achievements and results from the development of the Sherpa event-generation framework [2], targeted towards its application in top-quark physics at the LHC.

2 Fixed-order Matrix Elements

Central to accurate predictions for SM production rates, based on fixed-order perturbation theory, is the inclusion of higher-order corrections. Given that a huge variety of processes needs to be considered, for the dominant NLO QCD contributions these calculations have largely been automated in the framework of parton-level event generators. Within Sherpa automation is achieved through efficient tree-level matrix-element generators that also implement the construction of suitable infrared-subtraction terms in the Catani–Seymour dipole approach [3]. For the evaluation of the one-loop amplitude contributions interfaces to dedicated codes such as OPENLOOPS [4] and Recola [5] are employed. It remains the challenge to obtain results for very complex final states, in particular when featuring several QCD partons.

The first evaluation of NLO QCD corrections to $t\bar{t} + 3\text{jets}$ at the LHC have been presented in [6]. In Fig. 1 predictions for the jet-multiplicity and the $H_T^{jets}$ distribution in LHC collisions at $\sqrt{s} = 13$ TeV are shown. The NLO QCD results, evaluated for $\mu_{R/F} = H_T/2$, are compared to the corresponding LO estimates. Furthermore, results obtained using the Multi-scale Improved scale setting prescription at LO and NLO, dubbed MILO and MINLO, respectively, are presented. In both scale-setting schemes the uncertainty estimates, i.e. 7-point scale variations, indicated by the bands, reduce significantly at NLO. While for both observables the QCD corrections are rather flat for the scale choice $\mu_{R/F} = H_T/2$, in the MI scheme a shape distortion is observed. However, the NLO and MINLO results agree within 10%.
With the increasing precision of the LHC measurements, the inclusion of NLO electroweak (EW) corrections also becomes very relevant. Accordingly, there are strong ongoing efforts to extend the above mentioned methods for the automated evaluation of NLO corrections to the EW sector.

Figure 1: Inclusive $t\bar{t}+\text{jets}$ production at $\sqrt{s} = 13$ TeV with a minimum number $N_{\text{jet}} = 0, 1, 2, 3$ of jets with $p_{T,j} \geq 25$ GeV (left panel). Distribution of the total light-jet transverse energy for $pp \to t\bar{t} + 3$ jets production with $p_{T,j} \geq 25$ GeV (right panel). Figures taken from Ref. [6].

Figure 2: Transverse momentum distribution of the Higgs-boson (left panel) and the top-quark (right panel) in $pp \to t\bar{t}H$ at the LHC. Figures taken from Ref. [7].
Figure 3: **SHERPA** 4- and 5-flavour predictions for the top-quark transverse momentum distribution in \( t \)-channel single top production (left panel). Figure taken from Ref. [12]. Fixed-order and S-MC@NLO predictions for the two \( b \)-jet invariant mass in \( t\bar{t}b\bar{b} \) production (right panel). Figure taken from Ref. [13].

As an illustration, in Fig. 2 NLO QCD and EW predictions for the process \( pp \to t\bar{t}H \) evaluated with **SHERPA + RECOLA** [7] are shown. While the dominant corrections are of QCD type, in particular for high transverse momenta the EW corrections become sizable. The impact of yet higher-order EW corrections can be estimated by comparing their combination with the QCD result in additive and multiplicative manner. In particular for the top-quark transverse momentum the two variants agree nicely, indicating factorization of the EW corrections.

## 3 Matrix Elements and Parton Showers

To connect fixed-order parton-level QCD calculations with observable particle-level final states, parton-shower simulations prove to be an indispensable tool. Accounting for subsequent soft/collinear emission, they in turn resum logarithms of the ordering parameter guiding the evolution. In particular the combination of NLO QCD calculations, accounting for the \( O(\alpha_s) \) corrections already, requires non-trivial matching prescriptions, in order to preserve the NLO QCD accuracy for the inclusive production process. Furthermore, supplementing multi-parton processes with parton showers raises the problem of properly populating the emission phase space and consistently setting the multitude of scales appearing in the calculation. Furthermore, to properly account for the significant NLO QCD corrections observed for final states with increasing parton multiplicity necessitates means to consistently combine varying multiplicity contributions to an inclusive production process, *i.e.* merging algorithms.
$SHERPA+RECOLA$

$LHC$ $\sqrt{s} = 13$ TeV

$pp \rightarrow \ell^- \bar{\nu} j$

$NLO$ $QCD$

$LO$

$NLO$ $QCD + EW$

$NLO$ $QCD \times EW$

$10^{-9}$

$10^{-6}$

$10^{-3}$

$10^{3}$

$\frac{d\sigma}{dp_{T,W}} [fb/GeV]$

$10^{2}$

$10^{3}$

$0.5$

$1$

$1.5$

$3$

$p_{T,W} [GeV]$

$\sigma / \sigma_{NLO} QCD$

Figure 4: Fixed-order $QCD$ and EW predictions for the gauge-boson $p_T$ in $pp \rightarrow l^- \bar{\nu} +$jet production (left panel). Figure taken from Ref. [12]. Reconstructed transverse-momentum distribution of the gauge boson for various matrix element plus parton shower simulations, with and without considering EW corrections in the virtual approximation (right panel). Figure taken from Ref. [14].

In Fig. 3 recent examples of attaching the SHERPA dipole parton shower [8] to NLO QCD matrix elements are presented. In the left panel S-MC@NLO simulations of $t$-channel single top production in the 4- and 5-flavour scheme [9] are compared to ATLAS data [10]. The corresponding uncertainty bands correspond to scale and PDF variations, obtained using an on-the-fly event reweighting [11]. In the right panel fixed-order $QCD$ and S-MC@NLO predictions for the two $b$-jet invariant-mass distribution in $pp \rightarrow t\bar{t}b\bar{b}$ production are shown. The considered core process corresponds to $t\bar{t}b\bar{b}$ matrix elements. By invoking the parton shower a significant alteration of the $m_{bb}$ distribution is observed, having its source in the production of additional $b$-quarks in the shower evolution [13].

As exemplified in Fig. 2, EW correction often become sizable in phase-space regions of large transverse momenta. This is furthermore illustrated in the left panel of Fig. 1 for the process $pp \rightarrow W^- j \rightarrow l^- \nu j$. However, in these regions of phase space, e.g. at high-$p_T$ of the gauge boson in $pp \rightarrow W^- j$ production, QCD corrections from additional hard emissions are significant as well and should be considered in a realistic simulation. In the case of QCD corrections only, this is achieved through a merging prescription [15]. However, a generalization of these formalisms to NLO EW corrections is not yet available. Alternatively, EW corrections can be implemented in a QCD merging algorithm in an approximated manner. In Ref. [14] the approximation of just considering the virtual EW correction, dubbed $EW_{\text{virt}}$, has been studied for inclusive vector-boson production. This allows to include them as event-wise $K$-factors in the evaluation of the various Born-level contributions. In the right panel
of Fig. 4 corresponding predictions for merged samples with and without the EW$_{\text{virt}}$ contributions are compared. This approximation allows for particle-level predictions that include the full NLO QCD and the one-loop EW corrections for the various multiplicity processes contributing to inclusive vector-boson production.

4 Conclusions

Recent progress in the automated evaluation of higher-order QCD and EW corrections in the SHERPA generator framework have been presented. Particular emphasis was given to top-quark production processes at the LHC. Future developments will focus on improvements of the parton showers and the means to consistently combined them with NNLO QCD and NLO QCD and EW corrections.

References

[1] A. Buckley et al., Phys. Rept. 504 (2011) 145.
[2] T. Gleisberg et al., JHEP 0902 (2009) 007.
[3] T. Gleisberg and F. Krauss, Eur. Phys. J. C 53 (2008) 501.
[4] F. Cascioli, P. Maierhöfer and S. Pozzorini, Phys. Rev. Lett. 108 (2012) 111601.
[5] S. Actis et al., Comput. Phys. Commun. 214 (2017) 140.
[6] S. Höche et al., Eur. Phys. J. C 77 (2017) no.3, 145.
[7] B. Biedermann et al., Eur. Phys. J. C 77 (2017) 492.
[8] S. Schumann and F. Krauss, JHEP 0803 (2008) 038.
[9] F. Krauss, D. Napoletano, S. Schumann, Phys. Rev. D 95 (2017) no.3, 036012.
[10] M. Aaboud et al. [ATLAS Collaboration], Eur. Phys. J. C 77 (2017) no.8, 531.
[11] E. Bothmann, M. Schönherr, S. Schumann, Eur. Phys. J. C 76 (2016) no.11, 590.
[12] E. Bothmann, F. Krauss, M. Schönherr, arXiv:1711.02568 [hep-ph].
[13] F. Cascioli et al., Phys. Lett. B 734 (2014) 210.
[14] S. Kallweit et al., JHEP 1604 (2016) 021.
[15] S. Höche et al., JHEP 0905 (2009) 053.