

Recent progress on high order calculations and matching to parton showers

Emanuele Re^{a,1,*}

^aLAPTh, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS,
F-74940 Annecy, France

E-mail: emanuele.re@laphth.cnrs.fr

I give an overview of the recent progress on the matching of fixed-order calculations and parton showers. The focus is on the matching with NNLO QCD corrections as well as with NLO EW ones.

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*Speaker

1. Introduction

The current experimental precision reached by the LHC experimental collaborations (and even more the future prospects) requires theoretical predictions whose formal accuracy goes beyond the computation of NLO QCD corrections and their matching to parton showers (NLO_{QCD+PS}). Including (N)NNLO QCD corrections, and NLO EW ones (or combination thereof), is crucial, as often it is only through such predictions that a comparison between data and theory is made possible without being limited by the quality of theoretical predictions. In the rest of this review, I'll summarize the recent progress in the matching of NNLO QCD computations with parton showers (NNLO_{QCD+PS}), and in the inclusion of EW corrections in event generators.

2. Matching NNLO QCD corrections with Parton Showers

The issue of matching NNLO QCD corrections to parton showers has been already addressed by different groups, and NNLO_{QCD+PS} results have been obtained with four methods: “reweighted MiNLO” [1, 2], GENEVA [3, 4], UNNLOPS [5], MiNNLO_{PS} [6, 7].¹ Very schematically, the core ideas of these four methods can be summarized as follows:

- “reweighted” MiNLO' and MiNNLO_{PS} are based on the merging of NLO_{QCD+PS} results for $pp \rightarrow F$ and $pp \rightarrow F + j$ production, where F denotes a generic color-singlet final state. Such merging is obtained without any external resolution parameter, through the use of information known from transverse-momentum resummation.
- In GENEVA, one constructs IR-finite events using a resolution parameter (until recently, the “ N -jettiness” τ_N) whose resummation properties are accurately known, and that, through a cut (τ_N^{cut}), allows one to translate an “ M -parton” event to an “ N -jet” event. The extra radiation is provided by a parton shower, which needs to be constrained by a requirement on τ_N^{cut} .
- In UNNLOPS, one first promotes to NLO accuracy an “unitarized” CKKW approach, by carefully adding higher order contributions, and removing the pre-existing approximate terms at order α_s . The missing NNLO ingredients are then supplemented subsequently.

All the processes with 2 massless colored legs at LO can be described with NNLO_{QCD+PS} accuracy, and many results have been already obtained [2, 5–7, 11–28], including, in one case (based on the MiNLO' idea), results where NLO QCD accuracy was retained not only for the first jet, but also for the second one [29].

Besides the huge number of results for color-singlet production, in the last few months the first-ever NNLO_{QCD+PS} results for a process beyond color-singlet production were obtained: in Ref. [30] NNLO QCD corrections were matched to parton showers for top-pair production, through a non-trivial extension of the MiNNLO_{PS} method. Recent progress with the GENEVA method notably includes the first results obtained with a resolution parameter for the “0 to 1 jet” region other than τ_0 [25], where Radish results [9, 10, 31] for p_t resummation at N3LL were used as an input. In Ref. [32] the UNNLOPS method was generalized to take into account N3LO QCD corrections. Fig. 1 shows results for $t\bar{t}$ production (with MiNNLO_{PS}) and for the p_t spectrum of the Z boson in Drell-Yan production (with GENEVA).

¹After this talk was given, proof-of-concepts results using another NNLO_{QCD+PS} method were presented in Ref. [8].

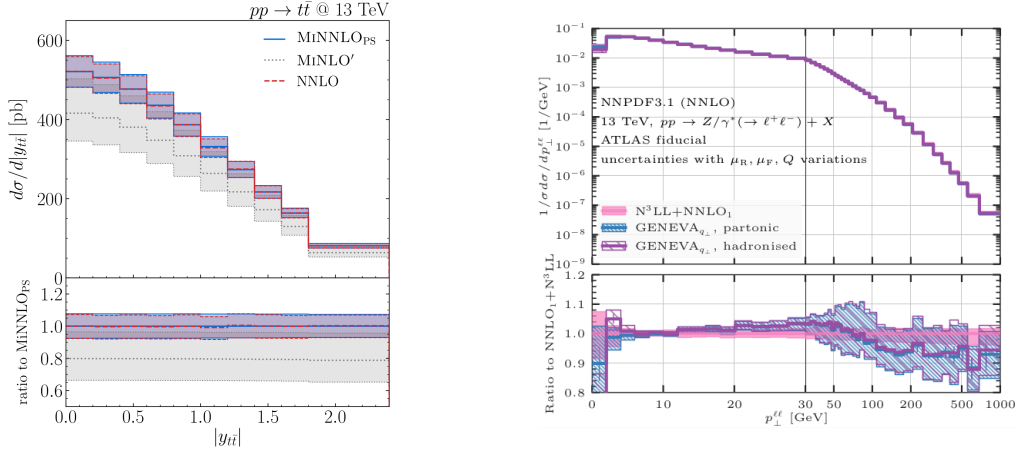


Figure 1: Left (supplemental material of Ref. [30]): comparison of NNLO (red), MiNLO' (gray), and MiNNLO_{PS} (blue) results for the $t\bar{t}$ rapidity in top-pair production. Right (Ref. [25]): comparison of the p_t spectrum of the Z boson in Drell-Yan production as obtained with GENEVA (blue and violet) and with Radish+NNLOJET (pink).

3. Matching NLO QCD and NLO EW corrections with Parton Showers

The computation of NLO EW corrections to multileg processes at the LHC can be considered a conceptually solved problem. Building up from NLO_{QCD}+PS methods, it is possible to match NLO EW corrections with parton showers (NLO_{EW}+PS), using different approaches that also allow, at least for simple processes, a simultaneous matching of QCD and EW corrections. Nevertheless, it is certainly true that a fully-general approach to tackle this challenge, and that is valid also for processes featuring QCD/EW interference at LO (as, for instance, $pp \rightarrow t\bar{t}$) is still missing, and it is one of the open problems in the field.

There are currently two approaches to get NLO_{QCD}+NLO_{EW}+PS results:

- One can include EW corrections through a local K -factor (which relies on the use of approximated integrated real contribution, and that acts on the “Born” configurations only) and by adding real QED radiation only through the parton shower. The main limitation of this scheme, at times denoted as EW_{VI} or EW_{virt}, and first proposed in Ref. [33], is that, formally, it is not valid for hard photon radiation. It has been successfully used, though, for several processes [33–37], and, notably, to incorporate approximate electroweak corrections in NLO_{QCD}+PS merged simulations [34, 35, 37].
- An exact matching of the EW corrections (both of virtual and real origin) can be obtained using the POWHEG-BOX-RES framework: this allows to include QCD and EW effects essentially through the traditional POWHEG approach, but also allowing for the generation of strong or electromagnetic real radiation from each resonance simultaneously. QCD and EW corrections are combined exactly (additively) at order α_s and α_{EW} , whereas factorizable and mixed $\alpha_s^n \alpha_{EW}^m$ terms are only included in the collinear limit. Such approach has been used in Refs. [38–40] and, previously, for Drell-Yan production, in Refs. [41–46].

Two recent applications of the above methods are related to diboson production processes (4ℓ production). Merged parton-shower predictions for $p \rightarrow WW$ and $pp \rightarrow WW + 1$ jet production, that include NLO QCD and EW corrections (the latter in the EWvirt approximation), were presented by the authors of Ref. [37]. In Ref. [40], QCD and exact EW corrections to all 4-lepton final states were instead matched to parton showers through the refinements of the POWHEG method as implemented in the POWHEG-BOX-RES framework. Fig. 2 displays a couple of representative results taken from Ref. [40] (left) and [37] (right).

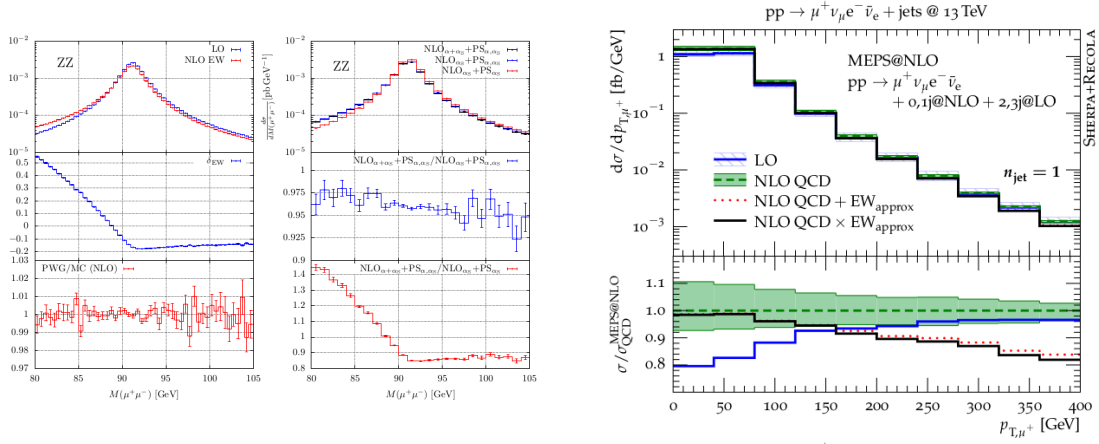


Figure 2: Left (Ref. [40]): Results, at different orders and approximations, for the invariant mass of the muonic pair in $pp \rightarrow e^+e^-\mu^+\mu^-$ production. Right (Ref. [37]): Results with and without EW effects for the muon transverse momentum in NLO merged predictions for $pp \rightarrow \mu^+\nu_\mu e^-\bar{\nu}_e + \text{jets}$.

Other schemes have been recently proposed to lift some of the limitations of the EWvirt approach: for instance, in Ref. [47], an EWSud scheme has been introduced, where LL and NLL EW corrections are included in the Sudakov limit [48], thereby allowing corrections to all jet multiplicities. In this context, even an hybrid scheme is being studied [49].

4. Conclusions

In this talk I summarized the recent activity in the context of matching parton showers with QCD fixed-order predictions at NNLO (NNLO_{QCD}+PS), and of the matching of QCD and EW corrections simultaneously (NLO_{QCD}+NLO_{EW}+PS).

Among the future challenges, certainly there is the NNLO_{QCD}+PS matching for a process with jets at LO, as well as the establishment of general method(s) to get NLO_{QCD}+NLO_{EW}+PS (and, eventually, NNLO_{QCD}+NLO_{EW}+PS) accuracy for processes featuring QCD/EW interference at LO.

The focus of this review was on matching aspects. The improvement of parton-shower algorithms has been, recently, a very active area in the field. Such activity covers several directions, spanning from the inclusion of EW effects in parton showers to the introduction of a new generation of parton shower algorithms whose accuracy goes beyond the leading logarithm. It is likely that the impact of such developments (the last one in particular) will be significant in the future. I refer to the talks given, for instance, at the workshop ‘‘Taming the accuracy of event generators’’ [50], for a recent overview of this activity.

References

- [1] K. Hamilton, P. Nason, C. Oleari and G. Zanderighi, *JHEP* **1305**, 082 (2013) [arXiv:1212.4504].
- [2] K. Hamilton, P. Nason, E. Re and G. Zanderighi, *JHEP* **1310**, 222 (2013) [arXiv:1309.0017 [hep-ph]].
- [3] S. Alioli, C. W. Bauer, C. J. Berggren, A. Hornig, F. J. Tackmann, C. K. Vermilion, J. R. Walsh and S. Zuberi, *JHEP* **09** (2013), 120 [arXiv:1211.7049 [hep-ph]].
- [4] S. Alioli, C. W. Bauer, C. Berggren, F. J. Tackmann, J. R. Walsh and S. Zuberi, *JHEP* **06** (2014), 089 [arXiv:1311.0286 [hep-ph]].
- [5] S. Höche, Y. Li and S. Prestel, *Phys. Rev. D* **91** (2015) no.7, 074015 [arXiv:1405.3607 [hep-ph]].
- [6] P. F. Monni, P. Nason, E. Re, M. Wiesemann and G. Zanderighi, *JHEP* **05** (2020), 143 [arXiv:1908.06987 [hep-ph]].
- [7] P. F. Monni, E. Re and M. Wiesemann, *Eur. Phys. J. C* **80** (2020) no.11, 1075 [arXiv:2006.04133 [hep-ph]].
- [8] J. M. Campbell, S. Höche, H. T. Li, C. T. Preuss and P. Skands, [arXiv:2108.07133 [hep-ph]].
- [9] P. F. Monni, E. Re and P. Torrielli, *Phys. Rev. Lett.* **116** (2016) no.24, 242001 [arXiv:1604.02191 [hep-ph]].
- [10] W. Bizon, P. F. Monni, E. Re, L. Rottoli and P. Torrielli, *JHEP* **02** (2018), 108 [arXiv:1705.09127 [hep-ph]].
- [11] A. Karlberg, E. Re and G. Zanderighi, *JHEP* **09** (2014), 134 doi:10.1007/JHEP09(2014)134
- [12] W. Astill, W. Bizon, E. Re and G. Zanderighi, *JHEP* **06** (2016), 154 [arXiv:1603.01620 [hep-ph]].
- [13] W. Astill, W. Bizoń, E. Re and G. Zanderighi, *JHEP* **11** (2018), 157 [arXiv:1804.08141 [hep-ph]].
- [14] E. Re, M. Wiesemann and G. Zanderighi, *JHEP* **12** (2018), 121 [arXiv:1805.09857 [hep-ph]].
- [15] W. Bizoń, E. Re and G. Zanderighi, *JHEP* **06** (2020), 006 [arXiv:1912.09982 [hep-ph]].
- [16] D. Lombardi, M. Wiesemann and G. Zanderighi, [arXiv:2010.10478 [hep-ph]].
- [17] D. Lombardi, M. Wiesemann and G. Zanderighi, [arXiv:2103.12077 [hep-ph]].
- [18] L. Buonocore, G. Koole, D. Lombardi, L. Rottoli, M. Wiesemann and G. Zanderighi, [arXiv:2108.05337 [hep-ph]].

- [19] S. Höche, Y. Li and S. Prestel, *Phys. Rev. D* **90** (2014) no.5, 054011 [arXiv:1407.3773 [hep-ph]].
- [20] S. Höche, S. Kuttimalai and Y. Li, *Phys. Rev. D* **98** (2018) no.11, 114013 [arXiv:1809.04192 [hep-ph]].
- [21] S. Alioli, C. W. Bauer, C. Berggren, F. J. Tackmann and J. R. Walsh, *Phys. Rev. D* **92** (2015) no.9, 094020 [arXiv:1508.01475 [hep-ph]].
- [22] S. Alioli, A. Broggio, S. Kallweit, M. A. Lim and L. Rottoli, *Phys. Rev. D* **100** (2019) no.9, 096016 [arXiv:1909.02026 [hep-ph]].
- [23] S. Alioli, A. Broggio, A. Gavardi, S. Kallweit, M. A. Lim, R. Nagar, D. Napoletano and L. Rottoli, *JHEP* **04** (2021), 254 [arXiv:2009.13533 [hep-ph]].
- [24] S. Alioli, A. Broggio, A. Gavardi, S. Kallweit, M. A. Lim, R. Nagar, D. Napoletano and L. Rottoli, *JHEP* **04** (2021), 041 [arXiv:2010.10498 [hep-ph]].
- [25] S. Alioli, A. Broggio, A. Gavardi, S. Kallweit, M. A. Lim, R. Nagar, D. Napoletano, C. W. Bauer and L. Rottoli, [arXiv:2102.08390 [hep-ph]].
- [26] S. Alioli, A. Broggio, A. Gavardi, S. Kallweit, M. A. Lim, R. Nagar and D. Napoletano, *Phys. Lett. B* **818** (2021), 136380 [arXiv:2103.01214 [hep-ph]].
- [27] T. Cridge, M. A. Lim and R. Nagar, [arXiv:2105.13214 [hep-ph]].
- [28] Y. Hu, C. Sun, X. M. Shen and J. Gao, [arXiv:2101.08916 [hep-ph]].
- [29] R. Frederix and K. Hamilton, *JHEP* **05** (2016), 042 [arXiv:1512.02663 [hep-ph]].
- [30] J. Mazzei, P. F. Monni, P. Nason, E. Re, M. Wiesemann and G. Zanderighi, *Phys. Rev. Lett.* **127** (2021) no.6, 062001 [arXiv:2012.14267 [hep-ph]].
- [31] W. Bizoń, X. Chen, A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, A. Huss, P. F. Monni, E. Re, L. Rottoli and P. Torrielli, *JHEP* **12** (2018), 132 [arXiv:1805.05916 [hep-ph]].
- [32] S. Prestel, [arXiv:2106.03206 [hep-ph]].
- [33] S. Kallweit, J. M. Lindert, P. Maierhofer, S. Pozzorini and M. Schönherr, *JHEP* **04** (2016), 021 [arXiv:1511.08692 [hep-ph]].
- [34] C. Gütschow, J. M. Lindert and M. Schönherr, *Eur. Phys. J. C* **78** (2018) no.4, 317 [arXiv:1803.00950 [hep-ph]].
- [35] M. L. Czakon, C. Gütschow, J. M. Lindert, A. Mitov, D. Pagani, A. S. Papanastasiou, M. Schönherr, I. Tsinikos and M. Zaro, [arXiv:1901.04442 [hep-ph]].
- [36] S. Kallweit, J. M. Lindert, S. Pozzorini and M. Schönherr, *JHEP* **11** (2017), 120 [arXiv:1705.00598 [hep-ph]].

- [37] S. Bräuer, A. Denner, M. Pellen, M. Schönherr and S. Schumann, *JHEP* **10** (2020), 159 [arXiv:2005.12128 [hep-ph]].
- [38] F. Granata, J. M. Lindert, C. Oleari and S. Pozzorini, *JHEP* **09** (2017), 012 [arXiv:1706.03522 [hep-ph]].
- [39] M. Chiesa, A. Denner, J. N. Lang and M. Pellen, *Eur. Phys. J. C* **79** (2019) no.9, 788 [arXiv:1906.01863 [hep-ph]].
- [40] M. Chiesa, C. Oleari and E. Re, *Eur. Phys. J. C* **80** (2020) no.9, 849 [arXiv:2005.12146 [hep-ph]].
- [41] L. Barze, G. Montagna, P. Nason, O. Nicrosini and F. Piccinini, *JHEP* **04** (2012), 037 [arXiv:1202.0465 [hep-ph]].
- [42] C. Bernaciak and D. Wackerroth, *Phys. Rev. D* **85** (2012), 093003 [arXiv:1201.4804 [hep-ph]].
- [43] L. Barze, G. Montagna, P. Nason, O. Nicrosini, F. Piccinini and A. Vicini, *Eur. Phys. J. C* **73** (2013) no.6, 2474 [arXiv:1302.4606 [hep-ph]].
- [44] C. M. Carloni Calame, M. Chiesa, H. Martinez, G. Montagna, O. Nicrosini, F. Piccinini and A. Vicini, *Phys. Rev. D* **96** (2017) no.9, 093005 doi:10.1103/PhysRevD.96.093005 [arXiv:1612.02841 [hep-ph]].
- [45] A. Mück and L. Oymanns, *JHEP* **05** (2017), 090 [arXiv:1612.04292 [hep-ph]].
- [46] M. Chiesa, F. Piccinini and A. Vicini, *Phys. Rev. D* **100** (2019) no.7, 071302 [arXiv:1906.11569 [hep-ph]].
- [47] E. Bothmann and D. Napoletano, *Eur. Phys. J. C* **80** (2020) no.11, 1024 [arXiv:2006.14635 [hep-ph]].
- [48] A. Denner and S. Pozzorini, *Eur. Phys. J. C* **18** (2001), 461-480 [arXiv:hep-ph/0010201 [hep-ph]].
- [49] E. Bothmann, talk at “Parton Showers and Resummation” 2021 (PSR 2021), <https://indico.cern.ch/event/1018828>
- [50] “Taming the accuracy of event generators”, <https://indico.cern.ch/event/999271/>