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New tools and parton shower for Higgs theoretical predictions

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We discuss the matching of NNLO fixed order calculations to parton shower programs in the context of Higgs physics at the LHC. We review different matching methodologies, including the MiNLO and Geneva approaches, and show results obtained for various Higgs production channels. In the case of Geneva , we outline the framework and discuss its recent application to the Higgsstrahlung process in which a Higgs is produced in association with a vector boson. We present differential distributions resummed at NNLL′ in the beam thrust and matched to the `PYTHIA` shower and find good agreement with the pure NNLO results for inclusive cases, while the description of other 0-jet-like resummation variables is improved beyond the parton shower approximation.

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1. Introduction

The measurement of the properties and couplings of the Higgs boson at the Large Hadron Collider is essential in order to verify that the Standard Model, in its current formulation, provides an accurate description of natural phenomena at the electroweak scale. In order to achieve this, experimental data must be compared with theoretical predictions which not only match the impressive precision reached by the various experiments, but which also model realistic final states of high multiplicity. While the former criterion can be met by exploiting the progress made in fixed order calculations, the latter can only be managed in the parton shower approximation. It is therefore desirable to combine the advantages of both types of calculation in a matching of the fixed order result to a parton shower.

At next-to-leading-order (NLO), the development of the `POWHEG` and `MC@NLO` methods for matching fixed order calculations to parton shower was followed by widespread implementation of said methods in several publicly available Monte Carlo event generators such as `MadGraph` and the `POWHEG BOX`. As a result, NLOPS predictions are available for essentially any Standard Model process of interest as well as for selected processes in Beyond the Standard Model theories and the Standard Model Effective Theory. The natural extension to this remarkable achievement is to promote the NLOPS matching to NNLOPS, which requires the invention of new techniques. In the literature, three different proposals have been made, each achieving the desired accuracy – they are known as UNNLOPS, MiNLO or MiNNLO$_{\mathrm{PS}}$, and the Geneva method. In this talk I will discuss recent progress in the application of the latter two methods to Higgs physics at the LHC with particular focus on the production of Higgs bosons in association with vector bosons, known as the Higgsstrahlung process.

2. The MiNLO approach and applications to Higgs physics

One potential route to a consistent NNLOPS matching is provided by the MiNLO approach. In Ref. [1], the authors took the `POWHEG` generator for Higgs production via gluon fusion in association with a jet, which is fully NLO accurate, and were able to extend its accuracy to cover configurations in which the jet has been fully integrated over, thus creating an event generator which is also NLO accurate for the inclusive case. This was possible via a clever choice of scales and the inclusion of Sudakov reweighting factors which improve the behaviour of the calculation at low p_T^H. Once this level of accuracy has been reached, the events can be reweighted to the NNLO Higgs rapidity distribution to produce a full NNLOPS-accurate generator for gluon-initiated Higgs production, which was accomplished in Ref. [2].

The Higgs transverse momentum spectrum from MiNLO before reweighting is shown in Fig. 1 alongside the fixed order prediction. Compared to the fixed order program Hnnlo, the various MiNLO predictions show improved behaviour in the low p_T region and exhibit the physical Sudakov peak. In the tail region, the authors verified that all predictions agree to within scale uncertainties.

The MiNLO approach was also applied to the production of W and Z bosons in association with a Higgs, otherwise known as the Higgsstrahlung processes [3, 4]. In the ZH case, the decay of the Higgs to a $b\bar{b}$ pair was also included at NLO and more recently a separate generator for

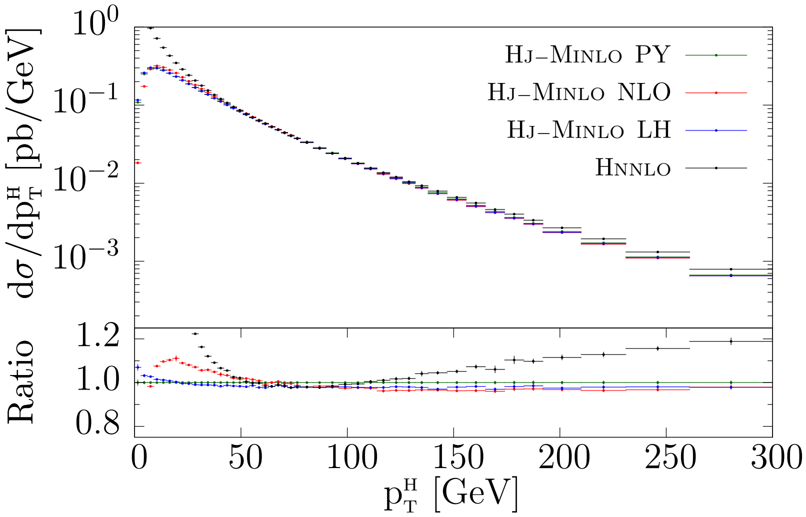

Figure 1: The transverse momentum of the Higgs boson as obtained via the MINLO method, before NNLO reweighting. The MINLO predictions are compared to a fixed order calculation. Figure from Ref. [2].

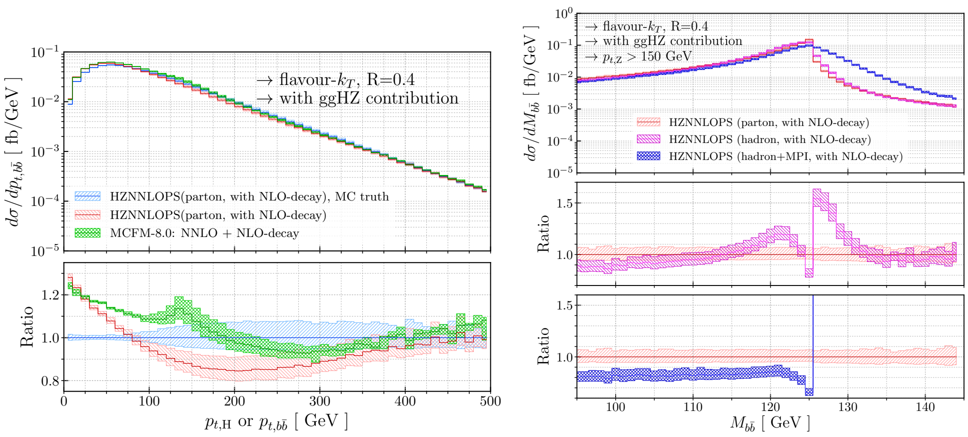

Figure 2: The invariant mass (left) and transverse momentum (right) of the $b\bar{b}$ pair in $Zb\bar{b}$ production as obtained via the MINLO method. Figure from Ref. [4].

$H \to b\bar{b}$ at NNLOPS using the same method has become available [5]. The reweighting to NNLO is slightly more involved in these cases compared to single Higgs production, since more Born variables are involved – nevertheless, the procedure remains consistent. In the left panel of Fig. 2, MINLO partonic predictions are compared to the fixed order to assess how well the Higgs is reconstructed from the $b\bar{b}$ pair. The right panel shows the invariant mass distribution of the $b\bar{b}$ pair at various stages of the showering – we see that hadronisation effects smear the distribution close to the peak, causing a dip at $M_{b\bar{b}} = M_H$.

In cases where the Born phase space is of high dimension, the NNLO reweighting of the MINLO approach poses technical limitations. Apart from the numerical demand, the discretisation of the reweighted observables into finite bin sizes reduces the applicability of the results when the binning is coarse, for example in tails of distributions. Since these are regions which are often targeted by experiments in new physics searches, this can pose a potential problem. In the recent MiNNLO$_{\text{PS}}$ approach [6], NNLO corrections are generated directly with no need for reweighting. This is made possible by making connection with the momentum space formula for q_T resummation and supplementing the Sudakov factors present in the MiNLO approach with the additional terms required to reach overall NNLO accuracy. At present, this has been demonstrated for the Drell-Yan process and Higgs production via gluon fusion. In Fig. 3, the transverse momentum and rapidity distributions of the Higgs from the MiNNLO$_{\text{PS}}$ method are compared to the MiNLO and fixed order results from the NNLO code MATRIX. In general good agreement between the MiNLO and MiNNLO$_{\text{PS}}$ results is seen, with an overall difference of ~ 8% between MATRIX and MiNNLO$_{\text{PS}}$ seen in the rapidity distribution that can be attributed to the large perturbative corrections present in the $gg \to H$ process.

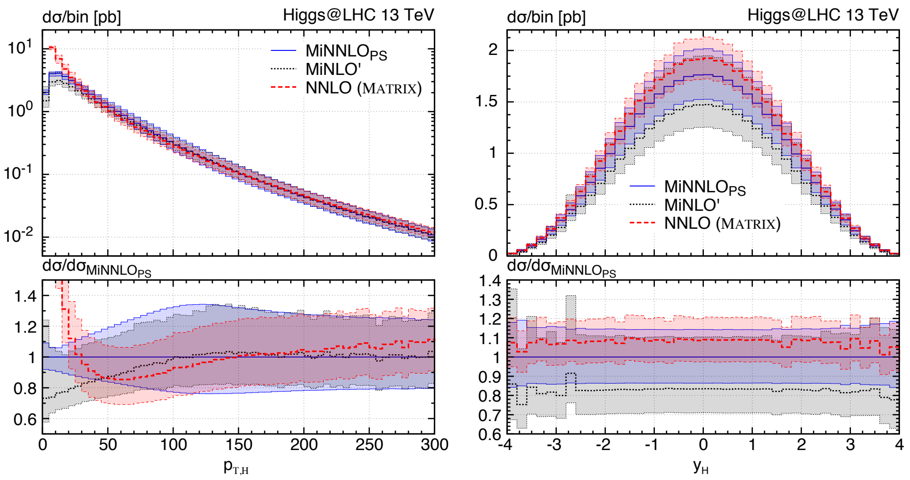

Figure 3: The transverse momentum (left) and rapidity (right) of the Higgs boson as obtained via the MiNNLO$_{\text{PS}}$ approach compared to the MiNLO results and the fixed order from MATRIX. Figure from Ref. [6].

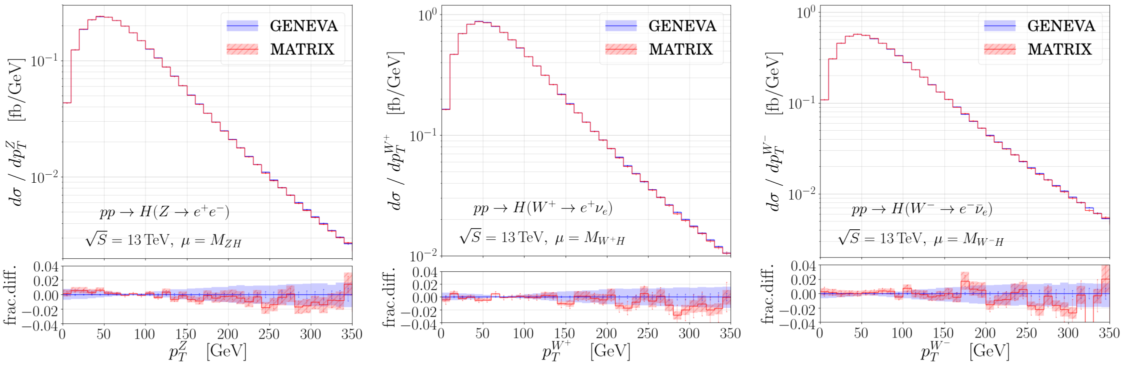

Figure 4: The transverse momentum of the vector boson in ZH, W^+H and W^-H production from left to right. Results from Geneva are compared with NNLO predictions from MATRIX. Figure from Ref. [11].

3. The GENEVA method and its application to the Higgsstrahlung processes

The GENEVA method [7] improves the NNLO calculation for a process of interest with next-to-next-to-leading logarithmic (NNLL′) resummation of a jet resolution variable before showering the events while maintaining the fixed order accuracy for the underlying process. The resummed element of the calculation is provided by a factorisation theorem derived from Soft Collinear Effective Theory which allows the logarithms of the jet resolution variable to be resummed at arbitrary order via renormalisation group evolution. The method was first tested on jet production in e^+e^- collisions [8] and later applied to the Drell-Yan process at the LHC [9, 10]. More recently, the Higgsstrahlung processes were implemented [11], marking the most complicated final state yet considered. In this section we shall briefly sketch the GENEVA method and then show results obtained for the Higgsstrahlung case.

The procedure for matching is as follows. First, infrared-finite events are defined based on a resolution variable. In practice, we have implemented the N-jettiness $\mathcal{T}_N$, which quantifies the extent to which a final state is N-jet-like, but other choices are in principle possible and are the subject of current development. For illustrative purposes, consider as a concrete example gluon-initiated Higgs production at NLO. We generate 0- and 1-parton events; those with a value of $\mathcal{T}_0$ below some defined cut are assigned to a 0-jet bin and any additional radiation is integrated over. Meanwhile, those 1-parton events with values of $\mathcal{T}_0$ above the cut are assigned to a 1-jet bin. The separation generalises to NNLO, at which point an additional resolution variable $\mathcal{T}_1$ must be introduced. We then associate differential cross sections to the events such that 0-jet events are NNLO accurate and resum the dependence on the resolution parameter at NNLL′ accuracy. We shower the events in such a way as to avoid spoiling the accuracy reached in the previous step, and may then add hadronisation effects or simulate multi-parton interactions.

Applying the GENEVA method to the Higgsstrahlung processes is a relatively simple extension of the Drell-Yan case – since the process factorises into a hadronic part which receives QCD corrections and an electroweak part which does not, the resummation elements from the Drell-Yan implementation can be recycled. At NNLO, the ZH process also receives a contribution from a loop-induced channel with gluons in the initial state. These diagrams are separately gauge-invariant and finite, and so we include these terms at fixed order only. Nevertheless, this has an important effect at the LHC due to the large gluon PDF and can change differential distributions by up to 20%. We neglect 2-loop contributions involving top quarks as these have shown to contribute to the total cross section only at $O(1\%)$ and their exact form remains unknown.

The validation of a selection of our results against the fixed order code MATRIX is shown in Fig. 4, where the transverse momenta of the vector bosons in the three processes are presented. We see good agreement with the NNLO results, to be expected for inclusive quantities such as these. In Fig. 5, the effect of including the loop-induced channel is shown and compared to the MATRIX result – again, agreement is good with the fixed order. We note the sizeable impact of the gluon contribution, which can affect the p_T^H distribution by up to 15%. The larger scale uncertainties can be attributed to the fact that the additional channel is included effectively only at LO, despite the fact that it is NNLO with respect to the quark induced channel.

In Fig. 6 we show inclusive distributions at various stages of the showering. We see that for inclusive observables, the effect of the shower on the partonic distributions is minimal and

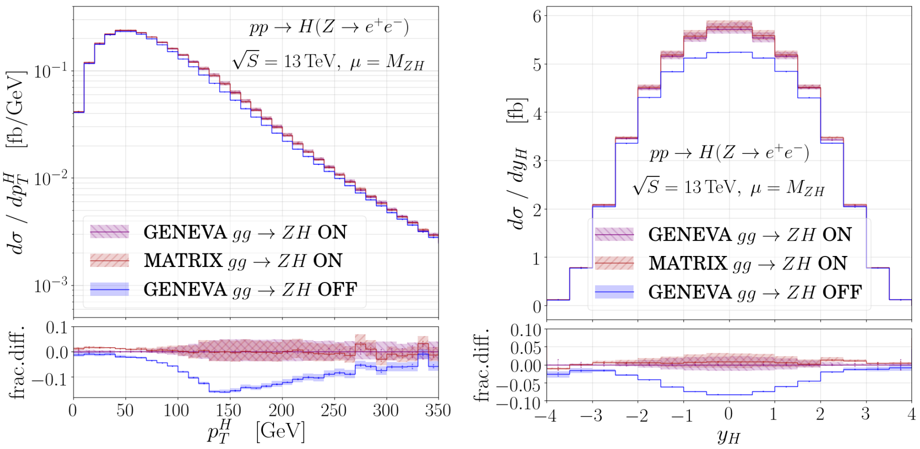

Figure 5: The transverse momentum and rapidity of the Higgs in ZH production, including the loop-induced gluon channel. Results from Geneva are compared with NNLO predictions from MATRIX. Figure from [11].

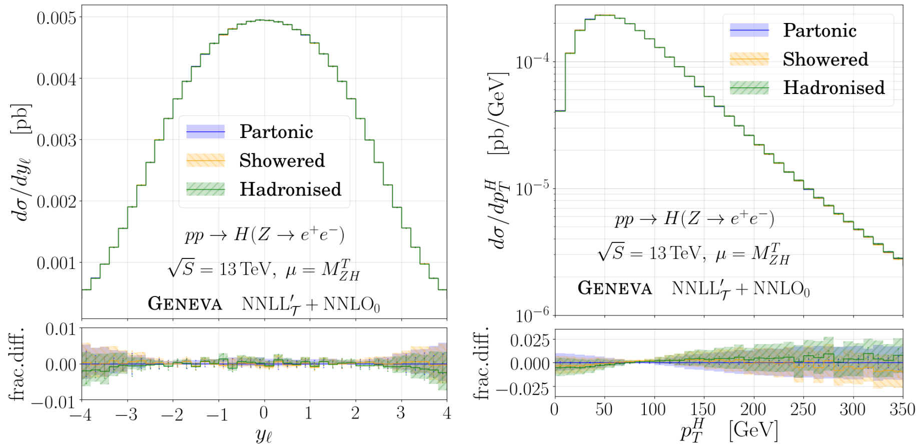

Figure 6: The rapidity of the hardest lepton and the transverse momentum of the Higgs in ZH production, at various stages in the shower process. Figure from Ref. [11].

that within scale uncertainties the distributions are largely unchanged and we are able to maintain NNLO accuracy. We observe larger effects in Fig. 7 where the shower causes an overall shift of the hardest jet rapidity distribution by $O(10\%)$, most likely due to the jet acceptance cut. The transverse momentum distribution of the VH system is also significantly modified in the resummation region by the shower. Fig. 8 shows the large effect of the shower on distributions when the gg channel is included, particularly in the hard region – this is likely due to our choice of a high starting scale for the shower for these contributions and has been noticed in studies of other gg-initiated processes.

4. Conclusions

We are continuing to extend the range of processes available in the Geneva framework. The results presented here for VH production have all assumed a stable Higgs boson, and a natural next

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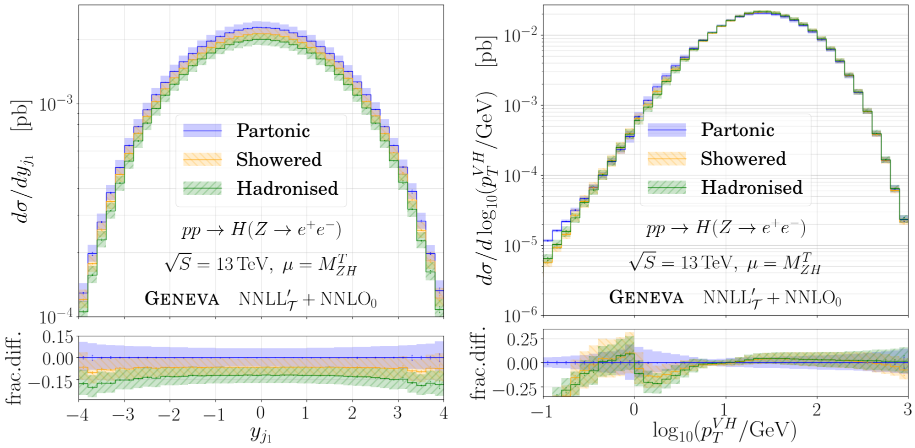

Figure 7: The rapidity of the hardest jet and the transverse momentum of the ZH system, at various stages in the shower process. Figure from Ref. [11].

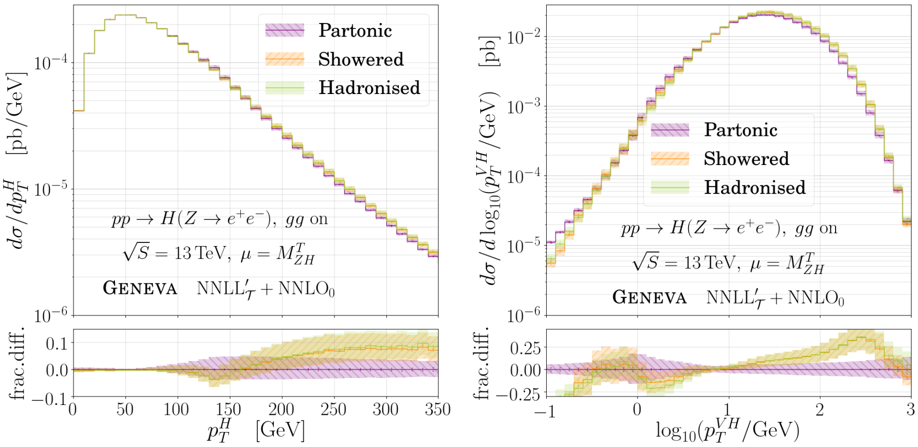

Figure 8: The transverse momenta of the Higgs and of the ZH system, at various stages in the shower process and with the gluon fusion channel contributions included. Figure from Ref. [11].

step is the inclusion of the Higgs decay. In particular the decay channel to b quarks is particularly relevant as this makes the greatest contribution to the recent experimental measurements and may allow the Yukawa coupling of the b quark to be probed. Our current work involves including the decay calculation at NNLO and resummed in thrust – this will allow production and decay to be combined within the narrow width approximation to provide a full NNLOPS $pp \to Vbb$ generator. Concerning Higgs physics, we are also working on implementing Higgs production via gluon fusion at NNLL′+NNLO. Other colour singlet processes are also under study such as diphoton and diboson production, and we are working on changing the resolution variable from N-jettiness to p_T. Clearly it is vital that we have event generators at high precision, and we hope that the experimental community will make use of our results.

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