PROCEEDINGS OF SCIENCE

NLL/NLO$^-$ studies on Higgs-plus-jet production with POWHEG+JETHAD

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We consider the semi-inclusive emission of a Higgs boson in association with a light-flavored jet separated by a large rapidity interval at the LHC. The accessed kinematic regimes fall into the so-called semi-hard sector, whose theoretical description lies at the intersection corner between the collinear factorization and the high-energy resummation. We present a prototype version of a matching procedure aimed at combining next-to-leading fixed-order (NLO) calculations from POWHEG with the resummation of next-to-leading energy logarithms (NLL) as obtained from JETHAD.

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1. Introductory remarks

With the discovery of the Higgs boson at the LHC a new era of precision tests of the Standard Model, as well as of intensive searches for clues of New Physics, began. In this respect, an accurate description of the gluon-gluon fusion channel in perturbative Quantum Chromodynamics (QCD) is of top priority [1, 2]. Higher-order calculations are necessary ingredients for precise studies of Higgs production *via* the well-grounded *collinear factorization*. Here, cross sections are elegantly cast as one-dimensional convolutions between collinear parton distribution functions (PDFs) and on-shell perturbative coefficient functions. At the same time, the theoretical description of Higgs-sensitive final states in the kinematic sectors accessible at the LHC and at future hadron and lepton colliders calls for the inclusion, to all orders, of logarithms which are systematically missed in a purely collinear vision. These logarithms can be large enough to spoil the convergence of the perturbative series, thus requiring the development of all-order *resummation* techniques.

In this study we consider the *semi-hard* QCD sector [3–5], where the rigorous scale hierarchy, $\sqrt{s} \gg \{Q\} \gg \Lambda_{\rm QCD}$ ($\sqrt{s}$ is the squared center-of-mass energy, $\{Q\}$ is a set of process-dependent hard scales, $\Lambda_{\rm QCD}$ is the QCD hadronization scale), brings to the growth of large energy logarithms. The Balitsky–Fadin–Kuraev–Lipatov (BFKL) resummation [6, 7] offers us a systematic way to resum to all orders these logarithms within the leading-logarithmic (LL) and the next-to-leading logarithmic (NLL) level (for recent advancements beyond NLL, see Refs. [8–11]). Remarkably, the BFKL formalism and its nonlinear extension to the saturation regime gives us a direct access to the gluon distribution in the nucleon at low-x [12–23]. Suitable reactions whereby testing BFKL and, more in general, high-energy dynamics in hadron collisions, feature the semi-inclusive emission of two objects possessing high transverse masses and being strongly separated in rapidity. On the one hand, transverse masses well above $\Lambda_{\rm QCD}$ make us fall into the semi-hard regime. On the other hand, a large final-state rapidity interval, ΔY, heightens the contribution of undetected gluons strongly ordered in rapidity, which are responsible for large logarithmic corrections.

A solid description of these two-particle hadroproduction channels calls for the employment of a *multilateral* formalism, where both the collinear and the high-energy dynamics come into play. To this extent, a *hybrid high-energy and collinear factorization* (HyF) was developed [24–26]. [*] HyF partonic cross sections take the form of a convolution between two impact factors (or emission functions), which are process dependent, and the NLL BFKL Green's function (analogous to the Sudakov factor of soft-gluon resummations), which is the process-universal part. Impact factors are in turn written as collinear convolutions between standard collinear PDFs and singly off-shell coefficient functions. The state-of-the-art accuracy of HyF is NLL/NLO. This means that, for a given process, the relevant coefficient functions need to be calculated at fixed next-to-leading order (NLO) accuracy. Otherwise, one must rely upon a partial next-to-leading treatment, labeled as NLL/NLO* when only the Green's function is taken at NLL and both the coefficient functions are at LO, or NLL/NLO$^-$ when the Green's function is at NLL, one coefficient function is at NLO, and the other one is at LO.

Promising semi-inclusive channels whereby probing the semi-hard QCD sector are: emissions of two Mueller–Navelet jets [32–39], multi-jet diffractive systems [40–44], Drell–Yan pairs [45–48], light [49–56] as well as singly heavy flavored [57–66] hadrons, quarkonium states [67–71], and

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[*] For similar approaches, close in spirit to ours, see Refs. [27–31].

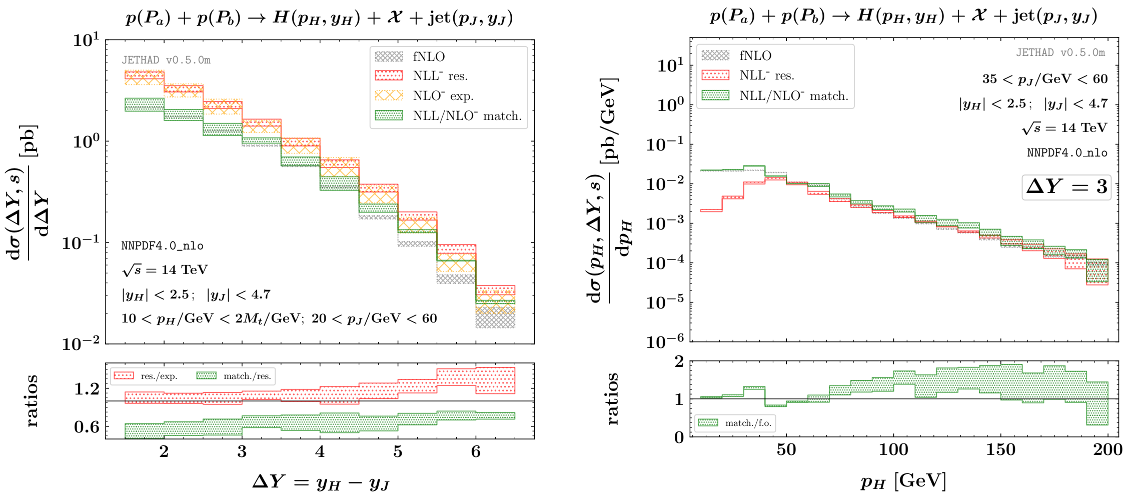

Figure 1: Higgs-plus-jet rapidity (left) and transverse-momentum (right) rates at $\sqrt{s} = 14$ TeV. Uncertainty bands reflect the variation of μ_R and μ_F scales in the $1 < C_\mu < 2$ range. Text boxes exhibit kinematic cuts.

exotic matter candidates [72]. In this article we consider the semi-inclusive Higgs-plus-jet process, which was studied in perturbative QCD within NNLO accuracy [73–75] and *via* the transverse-momentum resummation at the NNLL level [76]. As ΔY grows, the impact of energy logarithms becomes larger and larger. Thus, the high-energy resummation, as encoded in the HyF formalism, comes out as a valuable tool for a proper and consistent description of Higgs-plus-jet differential rates [24, 77, 78].

We present the POWHEG+JETHAD method, a prototype version of a novel *matching* procedure aimed at combining, in the context of Higgs-plus-jet rapidity and transverse-momentum distributions, next-to-leading fixed-order results with the resummation of next-to-leading energy logarithms. Results presented in the next section are for Higgs-plus-jet rapidity and transverse momentum spectra with the matching accuracy pushed to NLL/NLO$^-$ accuracy. They supersede the NLL/NLO* predictions of Ref. [79], but they are still preliminary, with a full NLL/NLO treatment being in preparation.

2. Higgs-plus-jet production: Matching NLL to NLO

An insightful information coming from quite recent, HyF-related studies on the Higgs transverse-momentum (p_H) spectrum in semi-inclusive Higgs-plus-jet emissions at the LHC, is the solid stability which this distribution exhibits under higher-order corrections and energy-scale variations. At the same time, however, large deviations of HyF predictions from the fixed-order background have been observed, their weight reaching roughly two orders of magnitude when $p_H \gtrsim 120$ GeV [24]. A similar trend has been shown by ΔY-distributions at LHC as well as nominal FCC energies [77].

This motivated us to develop a pioneering *matching* procedure between NLO fixed-order results and NLL-resummed calculations, which permits to exactly remove, within the NLL/NLO$^-$ accuracy, the corresponding *double counting*. Indeed, given that the full NLO contribution to the forward Higgs emission function was calculated only recently [80–83] and it has not yet been implemented in our reference technology, in the JETHAD code [70, 84, 85], we will rely upon a NLL/NLO$^-$ treatment. A sketch of our matching procedure reads

$$\underbrace{\mathrm{d}\sigma^{\mathrm{NLL/NLO}^-}(\Delta Y, \varphi, s)}_{\textbf{NLL/NLO}^-\ \texttt{POWHEG+JETHAD}} = \underbrace{\mathrm{d}\sigma^{\mathrm{NLO}}(\Delta Y, \varphi, s)}_{\textbf{NLO}\ \texttt{POWHEG}\text{ w/o PS}} + \underbrace{\underbrace{\mathrm{d}\sigma^{\mathrm{NLL}^-}(\Delta Y, \varphi, s)}_{\textbf{NLL}^-\ \textbf{resum}\ \text{(HyF)}} - \underbrace{\Delta\mathrm{d}\sigma^{\mathrm{NLL/NLO}^-}(\Delta Y, \varphi, s)}_{\textbf{NLL}^-\ \textbf{expanded}\ \text{at NLO}}}_{\textbf{NLL}^-\ \texttt{JETHAD}\text{ w/o NLO}^-\text{ double counting}} . \tag{1}$$

A given differential cross section, matched at NLL/NLO$^-$ (green) *via* the POWHEG+JETHAD method, takes the form of a sum of the NLO fixed-order contribution (gray) as obtained from the POWHEG technology [86–90] and the NLL$^-$ resummed part (blue) from JETHAD. The latter is given by the NLL$^-$ HyF resummed contribution (red) minus the NLL$^-$ expanded (orange) at NLO, *i.e.* without the doubly-counted term. Removing it from inside JETHAD instead of POWHEG makes our procedure dynamically compatible with other possible matching formalisms. More importantly, it allows us to discard spurious power-correction contaminations genuinely accounted for by HyF to all orders. We remark that POWHEG has been employed to calculate the fixed-order background, *i.e.* without adding *parton-shower* (PS) effects [91–96].

Figure 1 contains preliminary NLL/NLO$^-$ results for the ΔY (left) and p_H (right) spectra at 14 TeV LHC. Calculations were performed in the $\overline{\mathrm{MS}}$ scheme, and `NNPDF4.0_nlo` collinear PDFs were adopted [97, 98]. The color code in Fig. 1 matches the one of Eq. (1). Ancillary panels below primary plots show the reliability of our matching. In particular, focusing on the ΔY spectrum (left), the NLL-resummed contribution is very small when compared with the expanded term at low ΔY, while their ratio (red) generally increases with ΔY. Furthermore, the matched-over-resummed ratio (green) is smaller than one at low ΔY, and tends to one in the large ΔY range. All this clearly indicates that our matching is catching the core dynamics of our process, with the high-energy

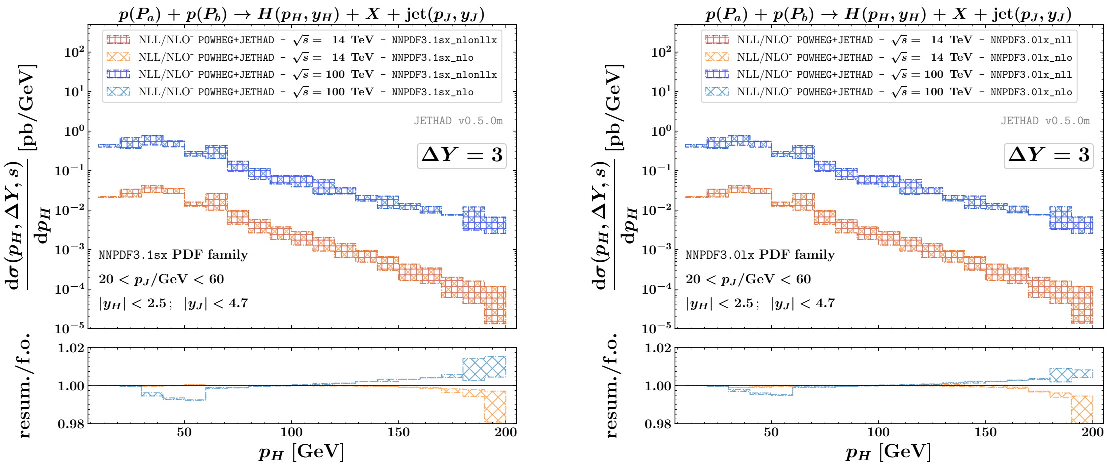

Figure 2: Higgs-plus-jet transverse-momentum rate at $\sqrt{s}$ = 14 TeV. Left (right) plot shows the impact of a resummation-based low-x (large-x) improvement on PDFs. Uncertainty bands reflect the variation of μ_R and μ_F scales in the $1 < C_\mu < 2$ range. Text boxes exhibit kinematic cuts.

resummation becoming more and more relevant as ΔY increases, as expected.

Figure 2 provides us with an additional analysis on the p_H spectrum, at $\Delta Y = 3$, and with small-x (left) or large-x (right) resummation improvements on collinear PDFs at 14 TeV LHC and 100 TeV FCC energies. Left panel is for p_H distributions obtained by making use of small-x resummed PDFs from the `NNPDF3.1sx` family [99], whereas right panel shows transverse-momentum rates obtained by means of large-x, threshold resummed PDFs from the `NNPDF3.0lx` one [100]. Ancillary panels below primary plots clearly indicate that the overall effect is relatively small, globally staying below 2%. For both resummations they are more pronounced and negative in the peak region, $30 \lesssim p_H/\text{GeV} \lesssim 60$, but only in the FCC case (turquoise), while they change sign in the large-p_H tail, being negative at LHC energies and then becoming positive at FCC ones. We stress that our study on the large-x improvement should be intended as a proxy for the effect of the threshold resummation [101–114] coming from PDFs only. To quantify the full impact of the threshold resummation on our high-energy observables, know to be sizable [52, 55, 84], one must develop a systematic method to resum large-x logarithms in our off-shell coefficient functions.

3. Conclusions and Outlook

We developed a prototype version of a matching procedure, relying on the POWHEG [86–90] and JETHAD [70, 84, 85] codes. Its purpose is combining NLO fixed-order calculations with the high-energy resummation at NLL. Future works will extend this study to: *a*) gauge the size of full NLO contributions [80–83], *b*) assess the weight of heavy-quark finite-mass corrections [115, 116], *c*) compare our predictions with PS [91–96] and HEJ [117, 118] inspired ones.

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