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Towards Higgs and Z boson plus jet distributions at NLL/NLO$^+$

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We present novel predictions for rapidity and transverse-momentum distributions sensitive to the emission of a Higgs boson accompanied by a jet in proton collisions, calculated within the NLO fixed order in QCD and matched with the next-to leading energy-logarithmic accuracy. We also highlight first advancements in the extension of our analysis to the Z-boson case. We come out with the message that the improvement of fixed-order calculations on Higgs- and Z-boson plus jet distributions is a required step to reach the precision level of the description of observables relevant for Higgs and electroweak physics at current LHC energies and nominal FCC ones.

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PoS(DIS2024)126

1. Introduction

To properly describe Higgs- and Z-boson production rates at the LHC as well as the future FCC, the *all-order* resummation of energy logarithms is relevant. In this study we turn our attention to the *semi-hard* sector, where the stringent scale hierarchy, $\Lambda_{\rm QCD} \ll \{Q_i\} \ll \sqrt{s}$, with $\{Q_i\}$ a set of typical hard scales and $\sqrt{s}$ the center-of-mass energy, leads to large energy logarithms. The Balitsky–Fadin–Kuraev–Lipatov (BFKL) resummation [1, 2] accounts for these logarithms within the leading-logarithmic (LL) and next-to-leading logarithmic (NLL) order. It also permits us to access the low-x gluon density in the proton [3–14]. Excellent probes of high-energy QCD in proton collisions are semi-inclusive productions of two particles tagged with high transverse masses and a strong rapidity separation, ΔY. To describe these two-particle reactions, a *multilateral* approach, where both collinear and high-energy dynamics are embodied, needs to be used. To this end, a *hybrid* factorization formalism (HyF) was built [15, 16] (see also [17–19] for single-particle emissions). HyF cross sections read as convolutions of two reaction-dependent emission functions and a universal NLL BFKL Green's function, which corresponds to the Sudakov radiator of soft-gluon resummations. Emission functions are in turn factorized as a convolution of collinear parton densities (PDFs) and singly off-shell coefficient functions. The highest accuracy of HyF is NLL/NLO: for a given reaction, the corresponding coefficient functions need to be calculated at fixed next-to-leading order (NLO) accuracy. Contrarily, one must rely on a partial next-to-leading level (NLL/NLO$^-$), with the Green's function taken at NLL, one coefficient function at NLO, and the other one at LO. The HyF formalism has been tested so far *via*: Mueller–Navelet jet tags [20–29], Drell–Yan pair [30, 31], light [32–38] as well as heavy-light [39–50] hadron, quarkonium [50–54], and exotic-matter [55–57] detections. Here we study Higgs-plus-jet rates [15, 58], which have been already investigated at next-to-NLO perturbative QCD [59–61] and by the next-to-NLL transverse-momentum resummation [62]. We present the POWHEG+JETHAD method, a novel procedure aimed at *matching* the NLO fixed-order with the NLL high-energy resummation.

2. Towards Higgs-plus-jet production at NLL/NLO

Preliminary HyF studies on the Higgs transverse-momentum (p_H) spectrum in the inclusive Higgs-plus-jet channel at LHC [15] and FCC [58] energies exhibited a solid stability under radiative corrections and scale variations. Nevertheless, a strong discrepancy between HyF predictions and the pure fixed-order background arose. For this reason, we developed a prime *matching* method between the NLO fixed order and the high-energy NLL resummation. It bases upon the exact removal, at the NLL/NLO$^-$ accuracy, of the corresponding *double counting*. Because the NLO Higgs emission function [63–65] still has to be implemented in the JETHAD code [54, 57, 66–68], we will rely upon a NLL/NLO$^-$ description. Our matching procedure reads as follows [69–71]

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

PoS(DIS2024)126

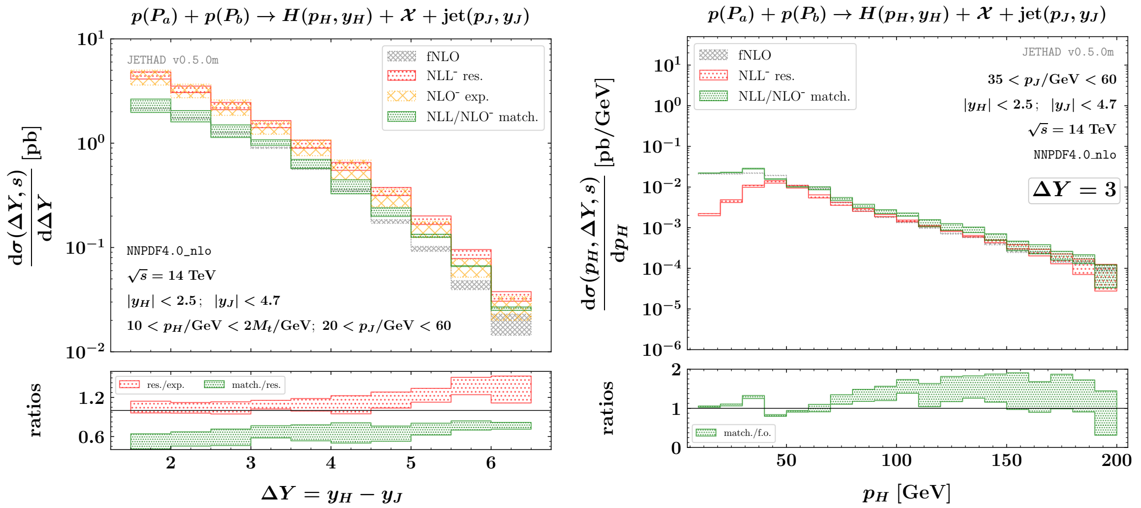

Figure 1: Higgs-plus-jet ΔY (left) and p_H spectrum at 14 TeV LHC energies. Uncertainty bands show $\mu_{R,F}$ variation in the $1 < C_\mu < 2$ range. Text boxes refer to kinematic cuts.

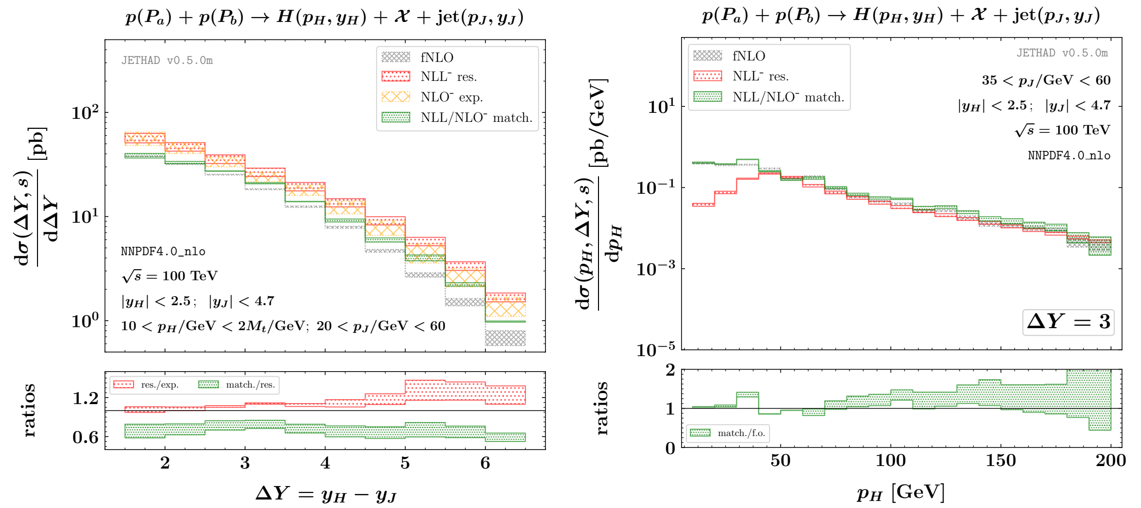

Figure 2: Higgs-plus-jet ΔY (left) and p_H spectrum at 100 TeV nominal FCC energies. Uncertainty bands show $\mu_{R,F}$ variation in the $1 < C_\mu < 2$ range. Text boxes refer to kinematic cuts.

An observable, $d\sigma^{\mathrm{NLL/NLO}^-}$, matched at NLL/NLO$^-$ (green) by the POWHEG+JETHAD method, is cast as a sum of the NLO fixed order (gray) from POWHEG [72–74] (without *parton shower* (PS) [75–77]) and the NLL$^-$ resummed part (blue) from JETHAD. The latter represents the NLL$^-$ HyF resummed term (red) minus the NLL$^-$ expanded one (orange) at NLO, *i.e.* without double counting. To extend our preliminary analysis presented in Refs. [69–71] we show 100 TeV FCC predictions for the ΔY spectrum (Fig. 2, left panel) and the p_H one at $\Delta Y = 3$ (Fig. 2, right panel).

The reliability of our matching procedure clearly emerges from the inspection of plots in our figures. Focusing on the ΔY spectrum (left plots), we notice that ratio between the NLL$^-$ resummed calculations and the NLO$^-$ expanded ones uniformly increases with ΔY, as highlighted by the ancillary panels below primary plots. This confirms that the effect of our high-energy resummation becomes more and more significant as we enter the large-ΔY regime. This trend is predicted by BFKL. Analogously, the ratio between the NLL/NLO$^-$ matched results and the NLL$^-$ resummed ones slowly tends to one as ΔY grows, thus corroborating the previous statement about the increasing weight of the resummation in the large rapidity-distance regime. This pattern is quite clear at 14 TeV, while it is less pronounced at 100 TeV. Concerning the p_H spectrum (right plots), we observe that the high-energy resummation corrects the fixed-order background of a factor 30% to 50% in the peak region, as shown by the matched/fixed-order ratio in the corresponding ancillary panels. This is in line with previous findings indicating that the p_H distribution is expected to receive large energy logarithmic corrections in the peak sector plus the first part of the spectrum tail, namely when the transverse momenta of the Higgs and the jet are roughly of the same order (see a related discussion in Section 3.2 of Ref. [15]). We also note that uncertainty bands of our matched results becomes wider and wider as p_H increases. Here, the impact of large DGLAP-type logarithms as well as *threshold* ones [78–80] becomes relevant, thus hampering the convergence of the high-energy series. However, at variance with results obtained in a pure HyF framework (see Fig. 8 of Ref. [15]), our NLL/NLO$^-$ matching procedure substantially reduces the discrepancy between the resummation and the fixed order in this region. This definitely leads to more precise and reliable BFKL-driven predictions of our Higgs-sensitive observables.

3. Conclusions and outlook

We proposed a new procedure, based on the POWHEG [72–74] and JETHAD [54, 57, 66–68] codes, aimed at matching NLO fixed-order predictions with the NLL energy resummation and beyond (NLL/NLO$^+$). Next steps will include: *a*) NLO contributions to the Higgs emission function [63–65], *b*) heavy-quark mass contributions [81, 82], *c*) the extension to the Z-boson case.

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PoS(DIS2024)126