Jet-veto efficiencies at all orders in QCD

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We present a next-to-leading logarithmic resummation for the jet-veto efficiency in Higgs production. We then discuss how this prediction affects the theoretical uncertainties in the region of transverse momenta of interest for Higgs searches at the LHC.

In searches of a Standard Model Higgs boson decaying into a pair of W bosons, it is customary to divide events with the requested signature into bins corresponding to different jet multiplicities [1, 2]. In particular, we concentrate on the 0-jet cross section, obtained by requiring that there are no jets with transverse momentum p_t larger than $p_{\rm t,veto}$. This 0-jet bin turns out to be less contaminated by W's originated from top-antitop production.

The 0-jet cross section can be computed at next-to-next-to-leading order (NNLO) thanks to the fully differential calculations for Higgs production of Refs. [3, 4]. The question then arises on how to estimate the theoretical uncertainties of the 0-jet cross section. It was already observed in Ref. [5] that simultaneous variation of renormalisation and factorisation scales leads to underestimating theoretical uncertainties, which even vanish for $p_{\rm t,veto} \simeq 25$GeV. Therefore, the authors of that paper propose a more sophisticated way to asses uncertainties based on those of the inclusive cross section. The authors of Ref. [6] argued further that the small scale uncertainty in the 0-jet cross section was due to cancellations between two effects of different physical origin. Indeed, $\sigma_{0-{\rm jets}}(p_{\rm t,veto}) = \sigma_{\rm inclusive} - \sigma_{\geq 1-{\rm jet}}(p_{\rm t,veto})$. While the inclusive cross section $\sigma_{\rm inclusive}$ is affected by a large K-factor, the one for having more than one jet $\sigma_{\geq 1-{\rm jet}}(p_{\rm t,veto})$ contains logarithmically enhanced contributions $\alpha_s^n \ln^m(M_H/p_{\rm t,veto})$, with $m \leq 2n$. Since these two effects are uncorrelated, they propose to estimate the uncertainties on $\sigma_{0-{\rm jets}}$ by just adding in quadrature the uncertainties on $\sigma_{\rm inclusive}$ and $\sigma_{\geq 1-{\rm jet}}$. We elaborate further on this idea and write the 0-jet cross section as the product of $\sigma_{\rm inclusive}$ and the jet-veto efficiency $\epsilon(p_{\rm t,veto})$, defined as the fraction of events such that all jets have a transverse momentum less than $p_{\rm t,veto}$. We argue that the knowledge of higher and higher orders for $\sigma_{\rm inclusive}$ does not help in reducing the uncertainty in $\epsilon(p_{\rm t,veto})$, which rather reflects our ignorance about logarithms $\alpha_s^n \ln^m(M_H/p_{\rm t,veto})$ of Sudakov origin, arising from a veto condition on real radiation. In the following we then consider the uncertainties on $\sigma_{\rm inclusive}$ and $\epsilon(p_{\rm t,veto})$ as uncorrelated and we concentrate on the efficiency only [7].

At fixed order, the efficiency is defined in terms of the following cross sections:

$$\begin{aligned} &\sigma_{\rm inclusive} \equiv \sigma = \sigma_0 + \sigma_1 + \sigma_2 + \dots\,, \\ &\sigma_{0-{\rm jets}}(p_{\rm t,veto}) = \Sigma(p_{\rm t,veto}) = \sigma_0 + \Sigma_1(p_{\rm t,veto}) + \Sigma_2(p_{\rm t,veto}) + \dots\,, \end{aligned} \tag{1}$$

where σ_i and $\Sigma_i(p_{\rm t,veto})$ are of relative order α_s^i with respect to the Born cross section σ_0. It is also useful to introduce the "complementary" cross sections $\bar{\Sigma}_i(p_{\rm t,veto})$ as follows

$$\bar{\Sigma}_i(p_{\rm t,veto}) = -\int_{p_{\rm t,veto}}^{\infty} dp_t \frac{d\Sigma_i(p_t)}{dp_t}\,, \qquad \Sigma_i(p_{\rm t,veto}) = \sigma_i + \bar{\Sigma}_i(p_{\rm t,veto})\,. \tag{2}$$

We remark that at the moment the perturbative expansion of these cross section is known up to relative order α_s^2. We now identify three schemes that we believe cover the possibilities to construct a jet-veto efficiency starting from the above cross sections:

$$\begin{aligned}
\epsilon^{(a)}(p_{t,\rm veto}) &= \frac{\sigma_0 + \Sigma_1(p_{t,\rm veto}) + \Sigma_2(p_{t,\rm veto})}{\sigma_0+\sigma_1+\sigma_2}\,,\\
\epsilon^{(b)}(p_{t,\rm veto}) &= \frac{\sigma_0 + \Sigma_1(p_{t,\rm veto}) + \bar{\Sigma}_2(p_{t,\rm veto})}{\sigma_0+\sigma_1}\,,\\
\epsilon^{(c)}(p_{t,\rm veto}) &= 1 + \left(1-\frac{\sigma_1}{\sigma_0}\right)\frac{\bar{\Sigma}_1(p_{t,\rm veto})}{\sigma_0} + \frac{\bar{\Sigma}_2(p_{t,\rm veto})}{\sigma_0}\,.
\end{aligned} \tag{3}$$

We observe that all these prescriptions differ only at order α_s^3. Each of them has its own meaning. Scheme (a) is the naive definition of the efficiency as the ratio between the 0-jet cross section and the inclusive cross section. Scheme (b) can be motivated by the fact that the jet-veto efficiency can be seen as one minus the probability of having one jet with $p_t > p_{\rm t,veto}$. This gives, at present accuracy, $\epsilon^{(b)}(p_{\rm t,veto}) = 1 - \sigma_{\geq 1-\rm jet}(p_{\rm t,veto})^{\rm NLO}/\sigma^{\rm NLO}_{inclusive}$. Finally, scheme (c) corresponds to the strict fixed order expansion of the efficiency.

In the following we use these three schemes as an extra handle, besides renormalisation and factorisation scale variations, to quantify the uncertainties on the jet-veto efficiency. Indeed, if we compute $\epsilon(p_{\rm t,veto})$ for the three schemes, we obtain very different predictions. Namely, including also independent variation of renormalisation and factorisation scale in the range $M_H/4 \leq \mu_R, \mu_F \leq M_H$ with $1/2 \leq \mu_R/\mu_F \leq 2$, in the region of interest for experimental studies ($p_{\rm t,veto} = 25$GeV for ATLAS and $p_{\rm t,veto} = 30$GeV for CMS), the spread in fixed-order predictions for the jet-veto efficiency is around 30% [7, 8]. This is not observed in Z production, where all three schemes basically coincide.

Since part of this bad convergence can be attributed to the presence of large logarithms of soft-collinear origin, it is useful to see how the uncertainty changes when performing an all-order resummation of such logarithms. At next-to-leading logarithmic (NLL) accuracy, which amounts in controlling all terms $\alpha_s^n \ln^n(M_H/p_{\rm t,veto})$ in $\ln\epsilon(p_{\rm t,veto})$, this is possible with the automated resummation program CAESAR [9]. In particular, if jets are to be found everywhere in rapidity, CAESAR tells us that the jet-veto efficiency is resummable within NLL accuracy, and has the form

$$\epsilon(p_{t,\rm veto}) \sim \mathcal{L}_{gg}(p_{t,\rm veto})\, e^{-R(p_{t,\rm veto})}\, \mathcal{F}(R')\,, \qquad R' = -\,p_{t,\rm veto}\frac{dR(p_{t,\rm veto})}{dp_{t,\rm veto}}\,, \tag{4}$$

where $\mathcal{L}_{gg}(p_{t,\rm veto})$ is the gluon-gluon luminosity, evaluated at the factorisation scale $p_{\rm t,veto}$, and $R(p_{\rm t,veto})$ is the Sudakov exponent

$$R(p_{\rm t,veto}) = 2C_A \int_{p_{t,\rm veto}^2}^{M_H^2} \frac{dk_t^2}{k_t^2}\frac{\alpha_s^{\rm CMW}(k_t)}{\pi}\left[\ln\frac{M_H}{k_t} - \frac{4\pi\beta_0}{C_A}\right]\,, \quad \beta_0 = \frac{11C_A - 4T_R n_f}{12\pi}\,, \tag{5}$$

where $\alpha_s^{\rm CMW}(k_t)$ is the physical coupling of Ref. [10]. While $R(p_{\rm t,veto})$ contains virtual corrections only, the function $\mathcal{F}(R')$ accounts for multiple soft-collinear real emissions. For a perfectly factorisable observable $V(k_1,\ldots,k_n) = \max_i\{V(k_i)\}$ we have $\mathcal{F}(R') = 1$. It turns out that, for small $p_{\rm t,veto}$, if jets are defined with a k_t^{2p}-algorithm (anti-k_t, Cambridge-Aachen, k_t), for emissions widely separated in rapidity no recombination can occur. Therefore, it is only the hardest gluon that contributes to the jet-veto efficiency, and therefore $\mathcal{F}(R') = 1$. A resummed prediction as the one in Eq. (4) contains an extra source of theoretical uncertainties. Indeed one can decide to resum $\ln(Q/p_{\rm t,veto})$ instead of $\ln(M_H/p_{\rm t,veto})$, where Q is an arbitrary "resummation" scale we choose to vary in the range $M_H/4 \leq Q \leq M_H$. Finally, to be able to present resummed predictions for the jet-veto efficiency, we have to match the efficiency in Eq. (4) with its expression at order α_s^2. Therefore, we introduce three matching schemes, defined in such a way that for $p_{\rm t,veto} \ll M_H$ the matched efficiency reduces to the expression in Eq. (4), whilst for $p_{\rm t,veto} \sim M_H$, it approaches its fixed order expression in any of the three schemes introduced in Eq. (3). The matching scheme gives us then an extra handle to estimate theoretical uncertainties.

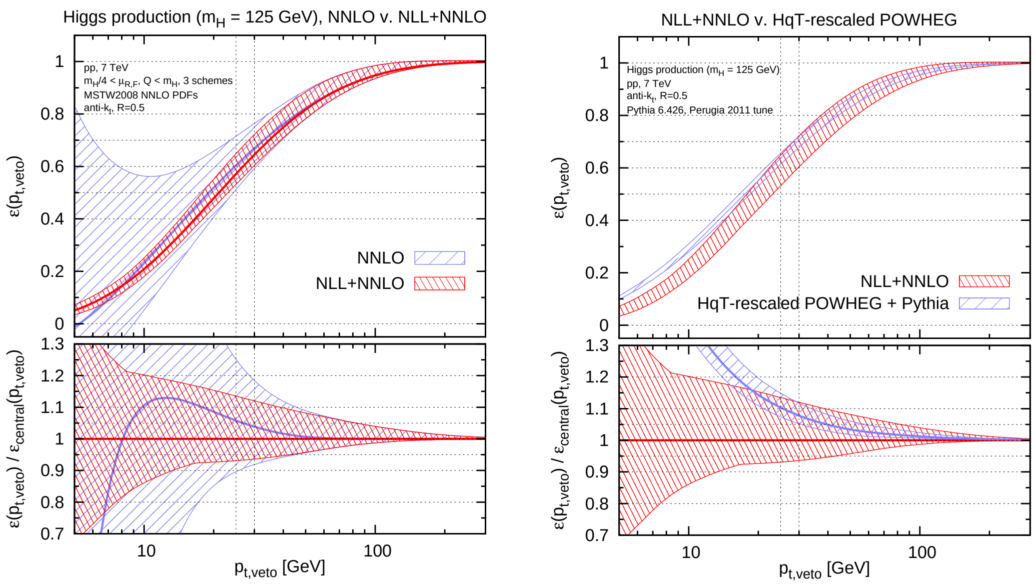

Figure 1: Left: the jet-veto efficiency for Higgs production at order α_s^2 (NNLO) and matched to NLL resummation (NLL+NNLO). Right: NLL+NNLO efficiency compared to POWHEG rescaled using HqT.

We now present results for the matched jet-veto efficiency, at the LHC with $\sqrt{s} = 7$ TeV, with jets clustered using the anti-k_t algorithm with $R = 0.5$, and for $M_H = 125$ GeV. In order to estimate theoretical uncertainties, we identify a "central" prediction, the efficiency computed with matching scheme (a) and with all scales Q, μ_R, μ_F equal to $M_H/2$. We then vary one scale at a time for scheme (a) in the range $[M_H/4, M_H]$, and vary the matching schemes using $Q = \mu_R = \mu_F = M_H/2$. In this way we believe we do not double count uncertainties. The predictions corresponding to this choice are shown in Fig. 1. We observe that NLL resummation helps reducing the uncertainties in the jet-veto efficency. Indeed, for $p_{\rm t,veto}$ between 25 and 30 GeV, they move from 20% (pure NNLO) down to 10% (NLL+NNLO). This improvement is not as huge, as is for lower values of $p_{\rm t,veto}$, and reflects the fact that in this intermediate region $\ln(M_H/p_{\rm t,veto})$ is not large enough to guarantee that resummation effects dominate. We notice also that here the uncertainty is dominated by the difference between matching schemes. Since this difference is formally NNNLL, we do not expect that a NNLL resummation could considerably help to reduce the theoretical uncertainty. Finally, we compare our predictions with the Monte Carlo event generator that is currently used by CMS and ATLAS to estimate the jet-veto efficiency. This is POWHEG [11] interfaced to PYTHIA [12], rescaled in such a way that it agrees with the Higgs p_t spectrum computed at NNLL+NNLO accuracy with the program HqT [13]. The uncertainties in POWHEG+PYTHIA are estimated by following the recommendation of Refs. [8, 14], i.e. varying renormalisation and factorisation scales independently around $M_H/2$ and fixing the parameter `hfact` to $h = M_H/1.2$. We observe good agreement between our NLL+NNLO and POWHEG+PYTHIA in the region of $p_{\rm t,veto}$ of interest. However, at lower values of $p_{\rm t,veto}$, we find that NLL+NNLO predictions tend to give lower efficiency than that obtained with POWHEG+PYTHIA. We remark that the same trend is observed when comparing NLL+NLLO to predictions obtained with other Monte Carlo event generators.

To conclude, we have investigated how a NLL resummation for the jet-veto efficiency affects the theoretical uncertainty on this quantity. It would be very interesting to see how these findings change after a NNLL resummation. In Ref. [7] we have computed (for $R < \pi$) the part of NNLL resummation that depends on the jet radius. The remaining NNLL contributions could be obtained by relating the jet-veto efficiency to the Higgs p_t spectrum (see for instance [15]). We hope to complete this study soon.

Note Added. The NNLL resummation for the jet-veto efficiency in Higgs and Drell-Yan production has been recently completed in Ref. [16].

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