JetVHeto: Higgs without jets

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We describe here the resummation of large logarithms that appear in exclusive Higgs cross-sections, with a veto on the presence of jets, both in the large top-mass limit and when finite mass effects are taken into account. We also present the efficiency-method to assign uncertainties to exclusive cross-sections.

1 Why jet-vetoes

After the Higgs discovery the focus of current experimental analyses at ATLAS and CMS is to measure its properties. These studies need accurate theory predictions for the Standard Model (SM) Higgs production cross-section including a reliable estimate of the associated theory uncertainty. The channel where the Higgs boson decays into $WW$ is particularly important for spin and coupling measurements, but it is plagued by a very large background from top production. The zero-jet bin has the lowest contamination of the $W$ bosons coming from top pair production, hence a veto on additional jets is a very effective way of reducing the background. The quantity of interest becomes then the exclusive zero-jet Higgs cross-section, i.e. the cross-section for events with no jets above a given $p_{t,veto}$, which in general depends on the jet-definition (jet-algorithm, radius $R$ and threshold $p_{t,veto}$).

Many searches and studies carried out at the LHC benefit from analyzing exclusive jet-bins since in general a veto on extra jets is widely used to suppress background from colored particles. In the following I will focus on the Higgs case, but methods here presented have more general scope. I will also discuss improved predictions for Higgs production in the presence of a jet veto when finite-mass effects are taken into account, and a generic procedure to assess theory errors for exclusive cross-sections.
2 Resummation

In the presence of a tight jet-veto a resummation is required. There are two ways to see this. One can inspect the explicit $\mathcal{O}(\alpha_s)$ calculation, which has the form

$$\sigma_{0-\text{jet}} \approx \sigma_0 \left( 1 + 2\frac{\alpha_s C_A}{\pi} \int \frac{d\omega}{\omega} d\theta^2 \left[ \Theta(p_{t,veto} - \omega \theta) - 1 \right] \right) \approx \sigma_0 \left( 1 - \frac{2 C_A \alpha_s}{\pi} \ln^2 \frac{m_H}{p_{t,veto}} + \ldots \right).$$

(1)

This result comes about because a tight veto on QCD radiation partially spoils the cancellation between real and virtual corrections, leaving behind large logarithms. Because of factorisation of soft-collinear QCD radiation, similar terms appear to all orders in $\alpha_s$ and need to be resummed whenever $p_{t,veto} \ll m_H$. An alternative way to see that fixed order calculations are unreliable at small transverse momenta is by looking at the scale variation uncertainty. For values of transverse momenta of interest by ATLAS and CMS ($p_{t,veto} \sim 25 - 30$ GeV) the scale variation underestimates the true uncertainty, since the relative exclusive uncertainty becomes smaller than that on the total cross-section. The reason is that there is a compensation between the large positive K-factor (in the total cross-section $\sigma_{\text{tot}}$) and the large negative logarithms in the zero-jet efficiency $\epsilon$, defined as the ratio of the zero-jet exclusive cross-section to the total cross-section. This accidental cancellation happens around the region relevant for ATLAS and CMS studies.

Next-to-leading logarithmic (NLL) resummed calculations for jet observables have been automated several years ago in numerical code CAESAR\textsuperscript{1}, provided the observable satisfies some applicability condition (e.g. recursive infrared and collinear safety, continuous globalness). It was observed some time ago that the jet-veto is within the scope of CAESAR. In fact at NLL the cross-section with a veto is just a pure Sudakov form factor.\textsuperscript{2} This observation paved the way to next-to-next-to-leading (NNLL) accurate resummations (sometimes also some terms beyond NNLL are included)\textsuperscript{3,4,5,6}.

While it is impossible to give all details here, I will try to outline the leading ideas. The first observation is that at next-to-leading order (NLO) the Higgs and leading jet traverse momentum coincide. Furthermore, at NLL there is no dependence of the zero-jet cross-section on the jet radius (since emissions are widely separated in rapidity). The idea then is to related the jet-veto resummation (which involves a finite jet radius) to the Higgs boson NNLL transverse momentum resummation\textsuperscript{7}. The NNLL dependence on the jet-radius has two sources: clustering of independent emissions and correlated emissions that end up in different jets. Both effects were computed first in ref.\textsuperscript{2}. The NNLL resummed integrated distribution takes then the form

$$\Sigma^{(J)}(p_{t,veto}) = \mathcal{L}_{gg}(p_{t,veto}) |M|^2_B e^{-R(p_{t,veto})} \delta F,$$

(2)

where the only difference with respect to the Higgs transverse momentum resummation formula lies in the last factor, the function $\delta F$ that accounts for soft-collinear multiple real emissions and contains all dependence on the jet radius. The other factors, the luminosity factor $\mathcal{L}_{gg}(p_{t,veto})$, the Born matrix element $|M|^2_B$, and the Sudakov form factor $e^{-R(p_{t,veto})}$ are in fact identical for the leading jet and Higgs transverse momentum resummation.

Other methods to obtain a NNLL resummations are based Soft Collinear Effective Theory (SCET) methods. In all approaches, the NNLL result is matched to NNLO to reproduce correct distributions also at large transverse momenta (following standard procedures).

3 Estimating the theory uncertainty: the efficiency method

A reliable but not overly conservative estimate of theoretical uncertainty is important when extracting properties or when setting exclusion limits. As discussed before a standard renormalisation and factorisation scale variation fails for exclusive cross-sections. Within the efficiency
method, exclusive cross-sections are written in the form
\[
\sigma_{0j} = \epsilon_0 \sigma_{\text{tot}}, \quad \sigma_{1j} = (1 - \epsilon_0) \epsilon_1 \sigma_{\text{tot}}, \quad \sigma_{2j} = (1 - \epsilon_0)(1 - \epsilon_1) \epsilon_2 \sigma_{\text{tot}}, \ldots. \tag{3}
\]
One takes as a working assumption that the total cross-section \(\sigma_{\text{tot}}\), which determines the normalisation and is plagued by large \(K\)-factors, and the efficiencies, that determine the shapes and contain large logarithms, are uncorrelated. Based on this, one writes down the covariance matrix in terms of uncertainties on the total cross-section and the efficiencies. We note that this method is different from the Stewart-Tackmann procedure \(^8\) that considers \(\sigma_{\text{tot}}\) and \(\sigma_{\geq 1j}\) as uncorrelated. We also remark that the efficiency method is general, simple also for high jet-multiplicities, and works seamlessly for resummed and fixed order calculations.

The input required for the efficiency method is the error on the total cross-section and on the efficiencies. For the total cross-section we use standard scale variation, use as a central scale \(m_H/2\) and vary independently the renormalisation \(\mu_R\) and factorisation scale \(\mu_F\) by a factor 2 up and down keeping \(1/2 < \mu_R/\mu_F < 2\). This results in seven scale choices. For the 0-jet bin (and similarly for other bins), we observe that for the efficiency at fixed order different definitions are possible and equivalent up to higher order terms (\(\text{N}^3\text{LO}\)), schematically:
\[
e^{(a)} = \epsilon_0^{\text{NNLO}} / \epsilon_{\text{tot}}^{\text{NNLO}}, \quad e^{(b)} = 1 - \frac{\sigma_{\geq 1j}^{\text{NLO}}}{\sigma_{\text{tot}}^{\text{NLO}}}, \quad e^{(c)} = \text{strict fixed order expansion}. \tag{4}
\]

For each of this fixed order efficiency definition, one can define a matching scheme that reduces to the corresponding fixed-order efficiency scheme (a, b, or c). One defines then the uncertainty on the efficiency as the envelop of varying \(\mu_R,\mu_F\) as for the total cross-section (which amounts to seven scale choices), for the central \(\mu_R,\mu_F\) scales one varies the resummations scale \(Q\) by a factor 2 up and down around \(m_H/2\) (this variation probes higher order logarithmic terms), and for central \(\mu_R,\mu_F\) and \(Q\) one varies the scheme used to define the efficiency (a, b or c). The reason for taking the envelope, rather than adding uncertainties in quadrature, is that the latter procedure is likely to double count some uncertainties. This procedure fully defines the input to our correlation matrix.

Figure 1 shows the uncertainty on the 0-jet cross-section at fixed order (left) and including a NNLL resummation (right) using the efficiency method (red) and with pure scale variation (green). It is evident that at fixed order the large band in the efficiency method properly reflects the large uncertainty of the calculation and that once a resummation is included, the efficiency method gives a marginally larger uncertainty compared to pure scale variation.

![Figure 1](image-url)

**Figure 1** – The zero-jet Higgs production cross-section as a function of the jet-resolution \(p_{t,\text{veto}}\) in the large \(m_t\) approximation at NNLO (left) and at NNLO+NNLL right. The green uncertainty band is obtained by varying only the renormalisation and factorisation scales (seven scale variation, see text), while the red band is obtained using the efficiency method.

4 Mass effects

All the above results have been obtained in the large-\(m_t\) approximation using an effective interaction of Higgs to gluons. Given the precision reached by theoretical predictions it is important
to establish whether exact top and bottom mass effects are negligible, or whether it is important to include finite-mass effects. A study based on POWHEG\textsuperscript{9} suggests that these effects are sizable and that bottom corrections give important corrections all the way to very large transverse momenta (10-20\% at about $p_t \sim 150$ GeV). This result is somehow surprising since diagrams with a gluon emitted from a bottom loop are suppressed both by the bottom-Yukawa coupling and by an explicit $m_b$ appearing from the helicity suppression in the loop integration. On the other hand in the region $m_b < p_t < m_H$ new (non-factorizing) logarithms of the form $m_b^2/m_H^2 \ln(m_b^2/p_t^2)$ appear in the amplitude. Therefore, including mass effects, the problem becomes a three scale problem ($m_b, m_H, p_t$). These new logarithms could be important and would need to be resummed to all orders, however their all order structure is not known. The observation is then that these logarithms vanish for $p_t \to 0$. Furthermore they are suppressed by $m_b^2$ (at least), hence their numerical impact should be small. They can then be treated as a finite remainder (which does not multiply the Born cross-section)\textsuperscript{10}. The resummation can then be matched to $\mathcal{O}(\alpha_4^2)$ as obtained from HNNLO\textsuperscript{11}, where $\mathcal{O}(\alpha_4^2)$ are obtained by taking the infinite mass result and rescale it by Born mass-correction factor. An alternative approach is to limit the resummation to the region $p_t < m_b$, use only the fixed order result for bottom-mass effects above it\textsuperscript{11}.

Fig. 2 shows a comparison of the prediction for the zero-jet cross-section at NNLL+NNLO in the infinite top-mass limit, including top corrections only, and including both top and bottom mass corrections. The band is obtained using the efficiency method presented earlier. While the finite top-mass effects amount to an overall rescaling by about 1.07, bottom-mass effects also distort the distribution, the overall effect is about -3\% at $p_t \sim 25 - 30$ GeV and about +2\% at high transverse momentum. These effects are well inside the uncertainty band of the large $m_t$ result.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{The zero-jet Higgs production cross-section as a function of the jet-veto in the large $m_t$ approximation (dot-dashed, green), including top max effects (dashed blue) and including top and bottom mass-effects (solid, red). The uncertainty band for the latter is obtained using the efficiency method.}
\end{figure}

\section{Conclusions}

The code JETVHETO can be downloaded from http://jetvheto.hepforge.org. Currently this code performs a NNLL+NNLO resummation the leading-jet transverse momentum\textsuperscript{a} and includes finite-mass effects. We use the efficiency method to estimate uncertainties, an approach that we

\textsuperscript{a}A resummation for the Higgs transverse momentum has been implemented as well, however it is valid in a restricted region where , in our approach there is an unphysical divergence at low $p_{t,H}$, and hence the NNLL resummation breaks down when approaching the divergence.
consider robust and reliable. We find that the resummation reduces considerably the uncertainty (by a factor 1.5-2 in the region of interest). The impact of mass-corrections is found to be moderate and similar for the jet and Higgs transverse momenta, but the inclusion of these effects increases the uncertainty slightly.

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References
