Higgs production via gluon fusion in k_T-factorisation

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Abstract. Theoretical studies of Higgs production via gluon fusion are frequently carried out in the limit where the top quark mass is much larger than the Higgs mass, an approximation which reduces the top quark loop to an effective vertex. We present a numerical analysis of the error thus introduced by performing a Monte Carlo calculation for $gg \to h$ in k_T-factorisation, using the parton shower generator `CASCADE`. By examining both inclusive and exclusive quantities, we find that retaining the top-mass dependence results in only a small enhancement of the cross-section. We then proceed to compare `CASCADE` to the collinear Monte Carlos `PYTHIA`, `MC@NLO` and `POWHEG`.

Keywords: Higgs, Monte Carlo, k_T-factorisation, Gluon Fusion
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INTRODUCTION

In the k_T-factorisation method [1–4] one makes the transition from parton-level to hadron-level cross-sections through a convolution with the *unintegrated* parton distribution functions [5, 6]. By retaining the dependence on the transverse momenta and evaluating the cross-section with off-shell incoming partons, the potentially large high-energy logarithms are automatically resummed.

Higgs boson production via gluon fusion is mediated through a top quark loop. In the *heavy-top* limit in which $2m_t/m_H \gg 1$ this loop can be replaced by an effective vertex, reducing the loop count by one and simplifying the calculation [7]. This approximation is frequently used in theoretical studies of the Higgs so a quantification of the error introduced is important. Numerical analyses in collinear factorisation indicate that the effects of the top-mass are small when $2m_t/m_H < 1$ [8–10].

The cross-section of the top-quark triangle with off-shell initial-state gluons, having first been derived in the heavy-top limit [11, 12], now exists in the literature with the full m_t dependence [13, 14]. It is therefore possible to examine the impact of this approximation on both inclusive and exclusive quantities, now within k_T-factorisation. A comparison of the cross-sections was carried out in Ref. [13, 15] concluding that on the inclusive level corrections are of the order of 5%. Through the use of the k_T-factorised Monte Carlo `CASCADE` [16, 17] we confirm this finding and extend the investigation to the spectrum of the mini-jet radiation accompanying the Higgs.

An additional question, conceptually separate from the heavy-top approximation, is the dependence of gluon radiation in association with Higgs production on the resummation of high energy corrections. We examine the impact of extra gluon radiation on the
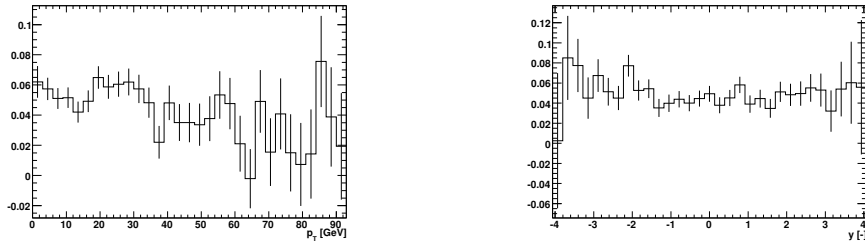
FIGURE 1. The quantity $1 - \frac{d\sigma(m_{\text{top}} \to \infty)}{dW} \Big/ \frac{d\sigma(m_{\text{top}})}{dW}$ is plotted for $W = p_T^{\text{Higgs}}$ (left) and $W = y^{\text{Higgs}}$ (right), where y is the rapidity. The error bars reflect only the statistical error of the Monte Carlo. These plots were obtained using the CCFM Set A [16, 22].

Higgs p_T spectrum by comparing `CASCADE` to the collinearly-factorised `PYTHIA` [18], `MC@NLO` [19] and `POWHEG` [20, 21].

All plots have been obtained for pp collisions at $\sqrt{s} = 14$ TeV and $m_H = 120$ GeV.

EFFECTS OF THE FINITE TOP-QUARK MASS

We find that retaining the full top-mass dependence in the matrix element leads to a small and approximately uniform increase in the differential cross-sections in p_T and y of the order of 5%. This is illustrated in Fig. 1 and is consistent with previous studies [13, 15].

We extend the study of top-mass effects by examining the mini-jet activity accompanying Higgs boson production. We follow the underlying event analyses of Ref. [23, 24], to which the reader is referred for the basic approach and motivation. We divide the azimuthal plane in four regions and accordingly classify the jets produced in association with the Higgs. Jets are defined using the `SISCone` algorithm [25] of the `FastJet` [26] package with $R = 0.4$ and $f = 0.5$, applied on the hadron level. We impose the cut $p_T^{\text{jet}} > 10$ GeV. The resulting multiplicity distributions in the four azimuthal regions are shown in Fig. 2, plotted against the Higgs transverse momentum. They appear to not be very sensitive to mass effects in the matrix element.

COMPARISON TO COLLINEAR MONTE CARLOS

We compare the effect of resumming higher-order contributions with a purely collinearly description of radiation. We extend the analysis of Ref. [23] where `CASCADE` was compared to the LO[1] Monte Carlo `PYTHIA` to include the collinear NLO generators `MC@NLO` and `POWHEG`. Showering in `MC@NLO` is performed through the angular-ordered `HERWIG` [27, 28] and we run `POWHEG` coupled to the `PYTHIA` shower. We operate `PYTHIA` with the 'new' underlying event model [29, 30] (`PYENVW`) using the 'Perugia 0' tune.

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[1] PYTHIA also implements partial radiative higher-order corrections.

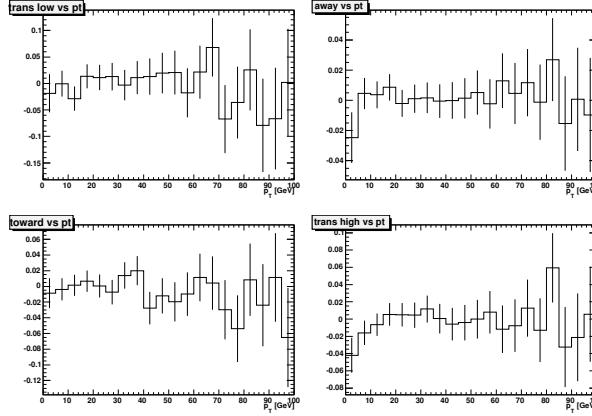**FIGURE 2.** The ratio $1 - \frac{dN(m_{\text{top}} \to \infty)}{dp_T} / \frac{dN(m_{\text{top}})}{dp_t}$ is shown, where N the number of mini-jets. The histograms are normalised to the p_T spectrum of the Higgs and thus do not scale with the cross-section.
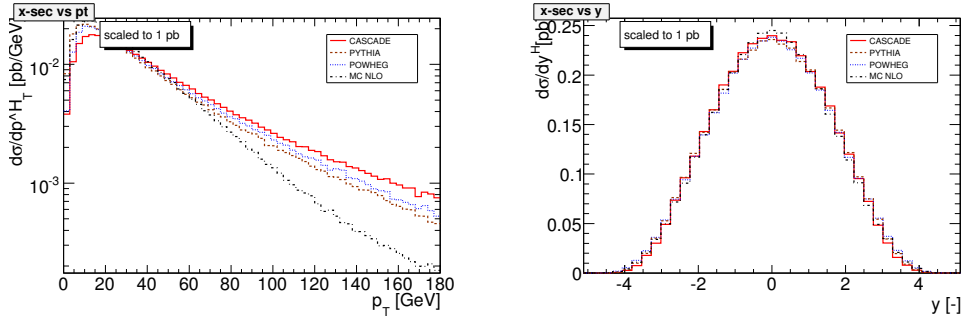

FIGURE 3. The p_T (left) and rapidity (right) spectrum of the Higgs. The curves have been scaled to a common token cross-section of 1 pb.

In order to make a baseline comparison with the collinear Monte Carlos we take $\text{ME}(\mathbf{k}_T) \to \text{ME}(\mathbf{k}_T = 0)\theta(\mu - k_T)$, where μ is the factorisation scale. We use unintegrated gluon distributions obtained from deconvolution of the ordinary distributions as described in Ref. [1]. We use a standard set implemented in CASCADE [16, 17]. For the collinear generators we used the CTEQ6M [31] set. The results are plotted in Fig. 3.

Additional corrections to the matrix element associated with the off-shellness contribute significantly to the spectrum. The details of this will be elaborated on in a forthcoming publication. We find that the details of the initial-state showering are important even in the high-p_T region.

CONCLUSION

We have implemented top-mass terms in the k_T-factorised Monte Carlo CASCADE. We have used this to analyse the uncertainty induced by the heavy-top approximation that is commonly used to simplify loop calculations. We have investigated this both for the inclusive cross-section and the multiplicity of mini-jets accompanying the Higgs boson.

Furthermore, we have examined the effect of the higher-order radiative terms resummed by k_T-factorisation on the Higgs p_T spectrum. We have compared `CASCADE` with the collinear Monte Carlos `PYTHIA`, `POWHEG` and `MC@NLO`. We find that the impact of both the unintegrated gluon distributions and matrix elements is significant even at p_T of the order or higher than the Higgs mass.

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