FERMILAB-PUB-11-528-T

Matched predictions for Higgs production via heavy-quark loops in the SM and beyond

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The main Higgs production channel at hadron colliders is gluon fusion via heavy-quark loops. We present the results of a fully exclusive simulation of gluon fusion Higgs production based on the matrix elements for $h + 0, 1, 2$ partons including full heavy-quark loop dependence, matched to a parton shower. We consider a Higgs with standard model couplings as well as models where the Higgs has enhanced couplings to bottom quarks (b-philic). We study the most relevant kinematic distributions, such as jet and Higgs p_T spectra and find that matched samples provide an accurate description of the final state. For the SM Higgs, we confirm the excellent accuracy of the large heavy-quark-mass approximation also in differential distributions over all phase space, with significant effects arising only at large p_T. For a b-philic Higgs however, the loops have a dramatic impact on the kinematics of the Higgs as well as of the jets and need to be accounted for exactly to achieve reliable event simulations.

PACS numbers: 12.38.Cy, 12.38.-t, 13.85.Qk, 14.80.Bn, 14.80.Ec

arXiv:1110.1728v1 [hep-ph] 8 Oct 2011

I. INTRODUCTION

The CERN Large Hadron Collider (LHC) is running at a center of mass energy of 7 TeV and it has already accumulated several inverse femtobarns of integrated luminosity per experiment. One of its main goals is to explore the details of electroweak symmetry breaking, and in particular to establish the existence of a Higgs sector of or beyond the Standard Model (SM).

At the LHC, Higgs boson production mainly proceeds via a quantum effect, gluon fusion (GF) [1]. This is induced by heavy-quark loops, in particular the bottom and the top quarks, the latter being by far the dominant one in the SM. For a not too heavy Higgs boson ($m_h \lesssim 2m_t$), and in appropriate kinematic regions ($p_T^h \lesssim m_t$), the top quark can be integrated out, resulting, to a very good approximation, in a simple, non-renormalizable effective field theory, $\mathcal{L}_{\rm HEFT} = -\frac{1}{4}\frac{h}{3\pi v}F^{\mu\nu,a}F^a_{\mu\nu}$ (HEFT) [2–4], v being the Higgs field vacuum expectation value and $F^{\mu\nu,a}$ the QCD field tensor. The next-to-leading order (NLO) QCD corrections [5–8] were calculated decades ago in both HEFT as well in the full SM and found to be very large ($\sigma^{\rm NLO}/\sigma^{\rm LO} \sim 2$). This motivated the formidable endeavour of the next-to-next-to-leading order (NNLO) QCD calculations, which have been fully evaluated in HEFT [9–11]. The exact NNLO calculation involves three loop massive diagrams, and is currently out of reach. However, recently, the finite top-quark mass effects to the total NNLO prediction have been estimated through a power expansion [12–15] and found to have a negligible impact on total rates. Soft gluon resummation effects have also been studied in HEFT at NNLL [16, 17]. On the other hand, it is known that in the hard tails of differential distributions or even in special kinematics regimes, such as at small-x [18], loop effects need to be accounted for exactly. So far, the recommended best predictions for Higgs GF inclusive production rates in the standard model [19] are based on the NNLO+NNLL results in HEFT, while keeping the heavy quark mass dependence at NLO+NLL [20].

In Beyond the SM (BSM) theories, GF becomes sensitive to all colored states in the spectrum with significant couplings to the Higgs(es). Even though the bookkeeping becomes more involved, as long as such states are heavy, an effective field approximation can still be used and QCD corrections can be computed as in the SM. The only genuine complication arises, not from additional heavy BSM particles, but from the possibility of bottom quarks to have enhanced couplings to the scalar (or pseudo-scalar) states of the theory. In SUSY, and more generally in type II two-Higgs-doublet-model scenarios, this corresponds to a large $\tan\beta$ scenario (where $\beta = v_1/v_2$, $v_{1,2}$ being the vacuum expectation values of the Higgs doublets coupling to down- and up-type fermions, respectively). In this case, the HEFT approximation cannot be employed and the accuracy of the best available predictions goes down to NLO [19].

Being of primary importance, total rates and Higgs kinematic distributions are now quite well predicted and also available via public codes such as ResBos [21] and HqT [22, 23]. Differential p_T^h distributions accurate to NLO can be also obtained via HIGLU [24] as well as via HPro [25], which both keep the exact bottom- and top-quarks mass loop dependence and therefore can be used also for predictions of scalar Higgs in BSM. However, in experimental analyses, it is also crucial to get as precise predictions as possible for exclusive observables that involve extra jets, such as the jet p_T spectra and the jet rates, at both parton and hadron level. To optimize the

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

search strategies and in particular to curb the very large backgrounds, current analyses both at Tevatron and at the LHC select 0-,1- and 2-jet events and perform independent analyses on each sample [26]. The final systematic uncertainties are effected by both the theoretical and experimental ones of such a jet-bin based separation, see, *e.g.*, Ref. [27]. In the HEFT, fully exclusive parton- and hadron-level calculations can be performed by Parton Shower (PS) programs such as PYTHIA [28], HERWIG [29] and SHERPA [30] in the soft and collinear approximation, or with NLO QCD codes matched with parton showers: via the MC@NLO [31] and POWHEG [32–35] methods. However, beyond the HEFT, no fully exclusive prediction has been available so far. The reason is that one needs to compromise between the validity of HEFT and the complexity of higher loop calculations. It is however possible to get full exclusive control at hadron level on the complex event topology at the LHC, while still reaching approximately NLL accuracy, with the help of recent sophisticated matching methods between matrix elements and parton showers [36, 37].

In PS programs, QCD radiation is generated in the collinear and soft approximation, using Markov chain techniques based on Sudakov form factors. Hard and widely separated jets are thus poorly described in this approach. On the other hand, tree-level fixed order amplitudes can provide reliable predictions in the hard region, while failing in the collinear and soft limits. To combine both descriptions and avoid double counting or gaps between samples with different multiplicity, an appropriate matching method is required. Several algorithms have been proposed over the years: the CKKW method, based on a shower veto and therefore on event re-weighting [36] and MLM schemes, based on event rejection [37, 38].

In this work, we report on the first matched simulation of Higgs production in gluon fusion that retains the full kinematic dependence on the heavy-quark loops, in the SM as well as in generic scenarios with enhanced Higgs couplings with bottom quarks, which we dub "b-philic Higgs".

The paper is organized as follows. We first describe our methodology. Then we present our results for a SM Higgs. We show that the matching procedure provides reliable results both at the Tevatron and especially at the LHC and that the effects from massive quark loops are indeed mild over all phenomenologically relevant phase space. The b-philic Higgs is considered in the following section, where it is shown that loop effects must be included exactly. Gluon fusion production is also compared to a matrix-element matched sample for $b\bar{b} \to h$, which is the dominant production mode in this scenario. We draw our conclusions in the last section.

II. METHOD

Our study is based on the k_T-MLM and shower-k_T matching schemes implemented in MADGRAPH/MADEVENT [39], interfaced with PYTHIA 6.4 for parton shower and hadronization. As explained below, we find it convenient to include the effects of the heavy-quark loop by simply reweighting the events generated via tree-level HEFT amplitudes.

In the k_T-jet MLM matching schemes [37, 40], matrix element multi-parton events are produced with a minimum separation k_T cutoff of $Q^{\rm ME}_{\rm min}$. For every event, the final-state partons are clustered according to the k_T algorithm, and the k_T value for each clustering vertex corresponding to a QCD emission is used as renormalization scale for α_S in that vertex. For the central hard $2 \to 1$ or $2 \to 2$ process, the transverse mass $m_T^2 = p_T^2 + m^2$ of the particle(s) produced in the central process is used as factorization and renormalization scale. Subsequently, this event is passed to the PYTHIA parton-shower generator. There, one of two schemes is employed. Either, the final partons (after parton showering) are clustered into jets, using the k_T algorithm with a jet cutoff of $Q^{\rm jet}_{\rm min} > Q^{\rm ME}_{\rm min}$. The jets are considered to be matched to the original partons if $k_T(\text{parton}, \text{jet})$ is smaller than the cutoff $Q^{\rm jet}_{\rm min}$. If any parton is not matched to a jet, the event is discarded. For events with parton multiplicity smaller than the highest multiplicity, the number of jets must be equal to the number of partons. We call this scheme the the k_T-MLM scheme. Alternatively, no matching between shower jets and partons is done. Instead, an event is retained provided that the hardest emission in the PYTHIA parton shower is below the scale $Q^{\rm jet}_{\rm min}$ (or, for events from the highest multiplity, below the scale $Q^{\rm parton}_{\rm min}$ of the softest parton in the event). This is called the "shower-k_T" scheme, and allows for the matching scale $Q^{\rm jet}_{\rm min}$ to be set equal to the matrix element cutoff scale $Q^{\rm ME}_{\rm min}$. The two matching schemes have been shown to give equivalent results [40], but for the case of b-philic Higgs, the shower-k_T scheme allows for lower matching scales and it is therefore more efficient.

In order to take into account the full kinematic dependence of the heavy quark loop in Higgs production, the full one-loop amplitudes for all possible subprocesses contributing to $h+0$, 1, 2 partons have been calculated. Analytic expressions have been generated with FeynArts 3.5 [41], and manipulated with FormCalc 5.3 [42]. The tensor integrals have been evaluated with the help of the LoopTools-2.5 package [42], which employs the reduction method introduced in Ref. [43] for pentagons, and Passarino-Veltman reduction for the lower point tensors. The resulting regular scalar integrals are evaluated with the FF package [44]. We have also implemented the reduction method for pentagon tensor integrals as proposed in Ref. [45] for better numerical stability. The codes have been used and validated against known results in a previous study [46]. The final implementation of the calculation includes the contributions from bottom and top quarks and their (destructive) interference. The evaluation of multi-parton loop amplitudes is, in general, computationally quite expensive. Moreover, in the case of inclusive matched samples, an ef-

	Cross section		
	Higgs mass [GeV]	Tevatron	LHC @ 7 TeV
$gg \to h$ (SM)	140	0.672 pb	12.2 pb
$gg \to h$ (SM)	500	0.003 pb	0.869 pb
$gg \to h$ (b-only)	140	3.0 fb	56 fb
$b\bar{b} \to h$	140	4.55 fb	135 fb

TABLE I: Reference values for total cross sections for Higgs production in the SM and considering only b-loops, used for the normalization of the inclusive samples. Results have been obtained via the HNNLO [47] and BBH@NNLO [48] codes, with $m_t = 173\,\text{GeV}$, $m_b = 4.6\,\text{GeV}$, $\mu_R = \mu_F = m_h$ and employing the MSTW2008NNLO pdf set [49].

ficient event generation needs as a first phase a rather thorough exploration of the phase space. It therefore becomes advantageous to devise a method where the mapping of the integrand can be done in a quick (though approximate) way and the evaluation of loops limited to a small number of points. Our strategy is as follows. Parton level events for $h + 0$, 1, 2 partons are generated via MadGraph/MadEvent in the HEFT model, with scale choices optimized for the subsequent matching procedure. Before passing them to the PS program, events are reweigthed by the ratio of full one-loop amplitudes over the HEFT ones, $r = |\mathcal{M}_{\text{LOOP}}|^2/|\mathcal{M}_{\text{HEFT}}|^2$. The reweighted parton-level events are unweighted, passed through Pythia and matched using the k_T-MLM or the shower-k_T scheme. All steps are automatic. To validate the matching procedure, the effect of changing the matching cutoff and other parameters such as $Q^{\text{jet}}_{\text{min}}$ and $Q^{\text{ME}}_{\text{min}}$ on several distributions, including the $n \to n-1$ differential jet rates have been extensively assessed.

Finally, we recall that even though matrix elements for up to two final states partons are included in the simulation, the accuracy of the overall normalization of the inclusive sample is only leading order, exactly as in a purely parton-shower result. It is therefore legitimate and consistent to adjust the overall normalization to the best available fully inclusive prediction for the corresponding process. To this aim, NNLO cross sections (in fact, just NLO for a b-philic Higgs) at the Tevatron and the LHC for the scenarios described below have been obtained via publicly available codes and collected in Table I.

III. SM HIGGS PRODUCTION

To illustrate the results of our simulations for the Tevatron and the LHC at 7 TeV for a standard model Higgs we show a few relevant observables in Figs. 1-3. We define jets via the k_T algorithm, with the distance measure between parton i and beam B, or partons i and j as $k_T^{i,B} \equiv$

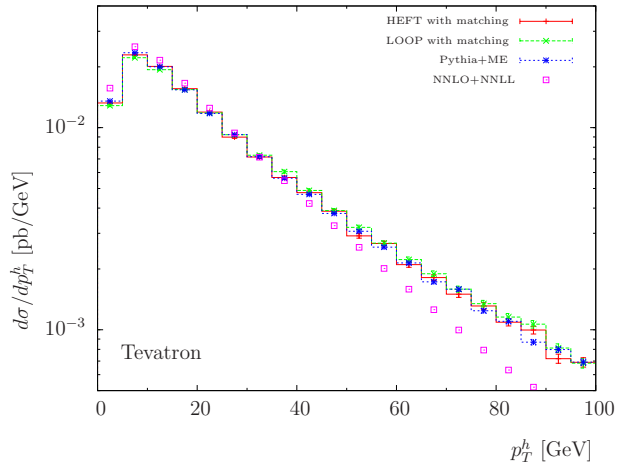

FIG. 1: SM Higgs p_T distributions for $m_h = 140\,\text{GeV}$ in gluon fusion production at the Tevatron. Results in the HEFT and with full loop dependence (LOOP) are compared to the default Pythia implementation (which accounts for $2 \to 2$ matrix element corrections) and to the NNLO+NNLL results as obtained by HqT [22, 23]. Curves normalized to the corresponding total cross sections of Table I.

$p_T^i,\ k_T^{i,j} \equiv \min\left(p_T^i, p_T^j\right)\sqrt{2(\cosh\Delta y_{ij} - \cos\Delta\phi_{ij})}/D$. Here y is the rapidity and ϕ is the azimuthal angle around the beam direction. The resolution parameter is set to $D = 1$. Jets are required to satisfy $|\eta_j| < 4.5$ and $p_T^j > 30\,\text{GeV}$. For sake of simplicity, we adopt Yukawa couplings corresponding to the pole masses, *i.e.*, for the top quark $m_t = 173\,\text{GeV}$ and for the bottom-quark mass $m_b = 4.6\,\text{GeV}$. Other quark masses are neglected. Throughout our calculation, we adopt the CTEQ6L1 parton distribution functions (PDFs) [50] with the core process renormalization and factorization scales $\mu_r = \mu_f = m_T^h \equiv \sqrt{(p_T^h)^2 + m_h^2}$. For the matching performed in MadGraph/MadEvent, the k_T-MLM scheme is chosen, with $Q^{\text{ME}}_{\text{min}} = 30\,\text{GeV}$ and $Q^{\text{jet}}_{\text{min}} = 50\,\text{GeV}$.

In Figs. 1 we show the Higgs p_T distribution for Standard Model Higgs GF production at the Tevatron with $m_h = 140$ in a range of p_T relevant for experimental analysis. We compare matched results in the HEFT theory and in the full theory (LOOP) with Pythia with $2 \to 2$ matrix element corrections. We also include the predictions from the analytic computation at NNLO+NNLL as obtained by HqT [22, 23]. The curves are all normalized to the NNLO+NNLL predictions. The three Monte-Carlo based predictions agree very well in all the shown range of p_T, suggesting that for this observable, higher multiplicity matrix element corrections (starting from $2 \to 3$) and loop effects are not important. This is the case also for jet p_T distributions (not shown) in the same kinematical range. The NNLO+NNLL prediction, on the other hand, suggests a slightly softer Higgs spectrum.

In Figs. 2-3, we show the Higgs and jet p_T distribu-

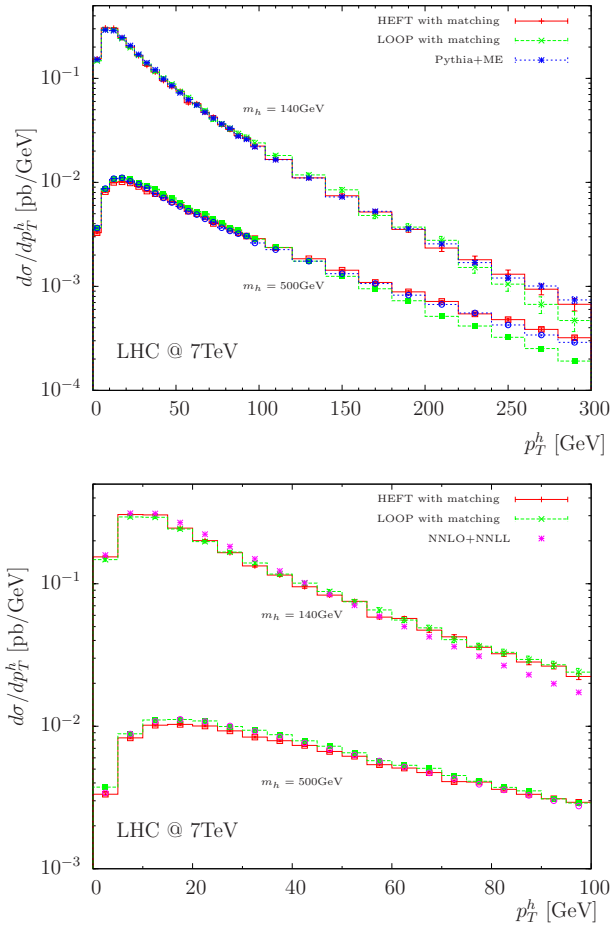

FIG. 2: SM Higgs p_T distributions for $m_h = 140\,\text{GeV}$ and $m_h = 500\,\text{GeV}$ in gluon fusion production at 7 TeV LHC. In the upper plot results in the HEFT and with full loop dependence (LOOP) are compared over a large range of p_T values to the default PYTHIA implementation, which accounts for $2 \to 2$ matrix element corrections. In the lower plot the low-p_T range is compared to the NNLO+NNLL results as obtained by HqT [22, 23]. Curves normalized to the corresponding total cross sections of Table I.

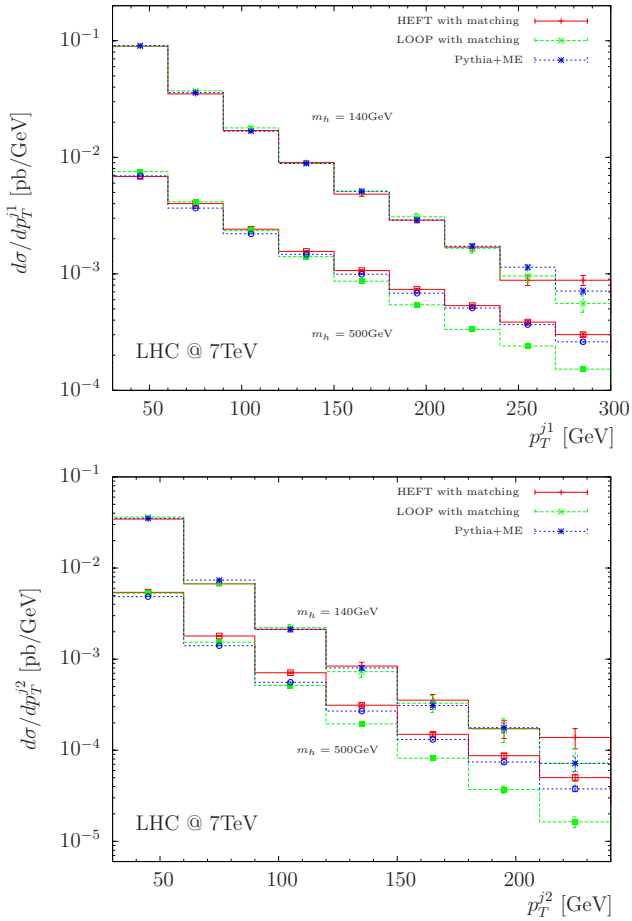

FIG. 3: Jet p_T distributions for associated jets in gluon fusion production of $m_h = 140\,\text{GeV}$ and $m_h = 500\,\text{GeV}$ Higgs bosons at 7 TeV LHC.

tions for Standard Model Higgs GF production at the 7TeV LHC with $m_h = 140$ and $500\,\text{GeV}$. Once again the Monte-Carlo based results agree well with each other. As expected, loop effects show a softening of the Higgs p_T, but only at quite high p_T. We also see that the heavier the Higgs, the more important are the loop effects. This is expected, since the heavy Higgs boson can probe the internal structure of the top-quark loop already at small p_T. The jet p_T distributions do confirm the overall picture and again indicate loop effects to become relevant only for rather high values of the p_T.

The agreement, on the other hand, of the NNLO+NNLL predictions at small p_T for both Higgs masses it is quite remarkable. In this respect, our analysis strongly motivates the use of matched samples for simulating GF Higgs production at the LHC. Key distributions, such as the p_T of the Higgs, do agree remarkably well with the best available predictions, for example NNLO+NNLL at small Higgs p_T, and offer improved and easy-to-use predictions for other key observables such as the jet rates and distributions. In addition, for heavy Higgs masses and/or large p_T, loop effects, even though marginal for phenomenology, can also be taken into account in the same approach, if needed.

IV. B-PHILIC HIGGS PRODUCTION

In this section we present the results of a simulation of a b-philic Higgs. Parameters are the same as in the previous section, except that, as explained below, the top Yukawa coupling is set to zero and the matrix-element matching in MADGRAPH/MADEVENT is performed through the shower-k_T matching scheme with $Q_{\text{match}} = 10\,\text{GeV}$.

In Fig. 4, we show the p_T^h distributions for GF production at the 7 TeV LHC of a b-philic Higgs with $m_h = 140\,\text{GeV}$. We remind the reader that in our cal-

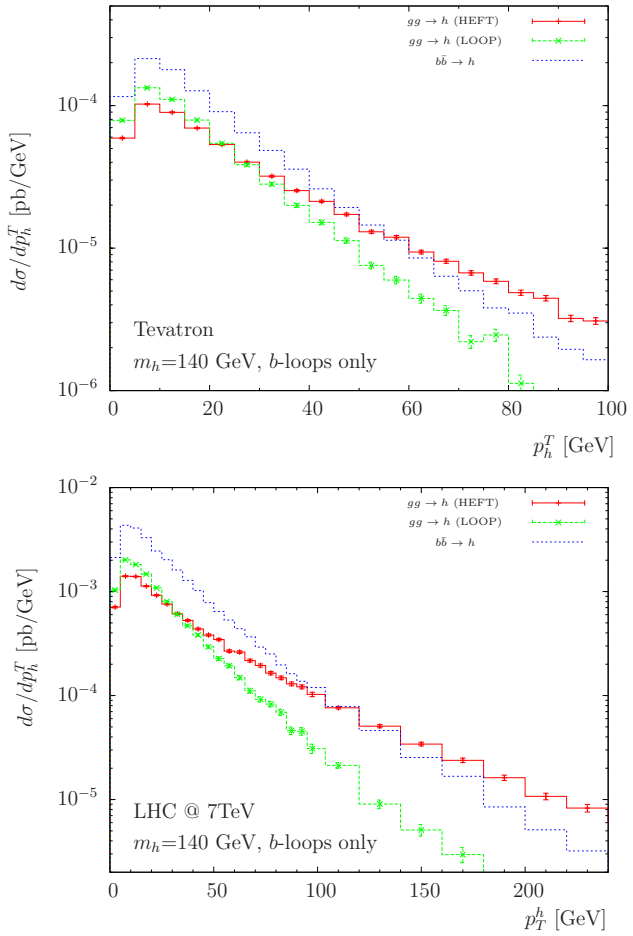

FIG. 4: b-philic Higgs p_T distribution a the Tevatron and the LHC with $m_h = 140\,\text{GeV}$. Results in the HEFT approximation (red curve) and with full loop dependence (green) are shown. Spectrum of Higgs produced via $b\bar{b}$ fusion in the five flavor scheme is also shown. All samples are matrix-element matched with up to two partons in the final state. Curves normalized to the corresponding total cross sections of Table I.

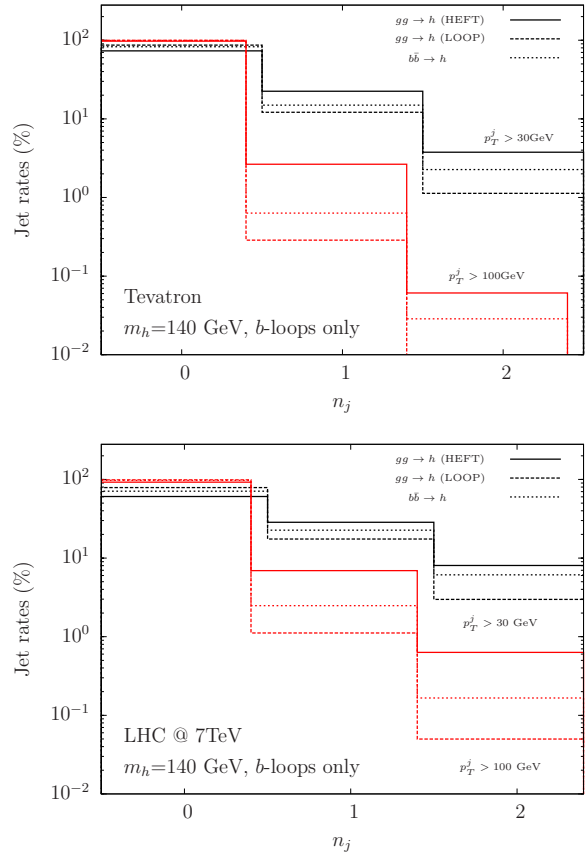

FIG. 5: Jet rates for b-philic Higgs production (where only the coupling to the bottom quark is included). $m_h = 140\,\text{GeV}$ at the Tevatron and LHC ($\sqrt{s} = 7$ TeV).

culation the bottom-quark and top-quark masses can be chosen independently as well as the value of the corresponding Yukawa couplings. We can therefore study the production of scalars with arbitrary couplings to the heavy quarks such as those appearing in a generic two Higgs doublet model or in the minimal supersymmetric standard model. For the sake of illustration, we define a simplified scenario where the Higgs coupling to the top quark is set to zero. In so doing, we study the Higgs and jet distributions relative to a "large $\tan\beta$" scenario with bottom-quark loops dominating. Note that for simplicity we keep the same normalization as in the standard model, i.e., $y_b/\sqrt{2} = m_b/v$ with $m_b = 4.6$ GeV, as the corresponding cross sections in enhanced scenarios can be easily obtained by rescaling.

In the b-philic Higgs production, the particle running in the loop is nearly massless, and there is no region in m_h or p_T where an effective description is valid. This also means that a parton-shower generator alone has no possibility of correctly describing the effects of jet radiation, and genuine loop matrix-elements plus a matched description are needed for achieving reliable simulations.

In fact, the largest production cross section for a b-philic Higgs does not come from loop induced gluon fusion, but from tree-level $b\bar{b}$ fusion. Phenomenologically, it is therefore very important to be able to also generate events for this kind of process, which typically leads to final states with more b-jets than the GF production. We do so by matching tree-level matrix elements for $h+0,1,2$ partons (with a $hb\bar{b}$ vertex) in the five flavor scheme to the parton shower. In so doing we provide a complete and consistent event simulation of inclusive Higgs production in a b-philic (or large $\tan\beta$) scenario. We note in passing that a four-flavor scheme, *i.e.*, starting from the leading order process $gg \to b\bar{b}h$, could also be employed. While this latter approach has some important advantages, it also offers complications with respect to the simpler five flavor scheme. A detailed comparison between the two approaches, which are known to be compatible at the level of total cross sections (see, *e.g.*, [19] and references therein), would certainly be welcome. Being beyond the

scope of this paper, however, we leave it to future work.

Fig. 5 shows jet rates for the Tevatron and 7 TeV LHC for a b-philic Higgs for two minimum jet p_T^j scales, 30 and 100 GeV. As is readily seen from the figure, the effect of properly including loop effects is significant already with a jet p_T^j cutoff at 30 GeV, and increasingly important for larger cutoff values. This immediately translates to the effect of a jet veto with a given p_T^j cutoff for the veto.

V. CONCLUSIONS

In summary, we have presented the first fully exclusive simulation of gluon fusion inclusive Higgs production based on the exact one-loop matrix elements for $h + 0, 1, 2$ partons, matched to PYTHIA parton showers using multiple matching schemes implemented in MADGRAPH/MADEVENT. We have compared the loop reweighted matched results with the corresponding HEFT results, PYTHIA results, and, when possible, with NNLO+NNLL predictions. We have considered both the SM Higgs and the case of scalar particles with enhanced couplings to bottom quarks and studied the most relevant kinematic distributions, such as jet and Higgs p_T spectra. Our results highlight the relevance of a complete loop calculation at large p_T for a standard model Higgs and in all phase space for b-philic Higgs. Such improved simulations might be particularly relevant in searches performed via multivariate analysis techniques where details about the kinematic distributions of the Higgs decay products and accompanying jets can have significant impact on the results.

We conclude by stressing that the method employed in this work, *i.e.*, using tree-level amplitudes based on an effective theory to generate parton-level events and then reweighting them by the exact loop amplitudes before matching to the shower, is completely general and can therefore be applied to any loop-induced process. Work towards the automatization of this approach in MADGRAPH 5 [51] via MADLOOP [52] is in progress.

Acknowledgments

We thank Paolo Torrielli, Simon de Visscher, Massimiliano Grazzini and Giuseppe Degrassi for helpful discussions. This work is supported by the European Community's Marie-Curie Research Training Network HEPTOOLS under contract MRTN-CT-2006-035505, US DOE Contract No. DE-AC02-07CH11359, by the National Natural Science Foundation of China, by the IAP Program, BELSPO P6/11-P and the IISN convention 4.4511.10.

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