

Study of theoretical uncertainties in Higgs production from Monte Carlo event generators and analytic calculations

Simone Lionetti, Università degli Studi di Milano

September 7, 2012

Abstract

We investigate the possibility of a comparison between resummed results from Monte Carlo event generators and analytic calculations. We consider the case of the beam thrust distribution in Higgs production via gluon fusion at the LHC, where both resummation of Sudakov double logarithms and fixed-order corrections are important. The parameter variations that can be exploited to obtain uncertainty bands in the case of the HERWIG++ parton shower are related to the scale variations used to analytically measure the size of higher-order corrections. Two different parton shower algorithms are considered, and next-to-leading order matched calculations in the POWHEG and MC@NLO schemes are examined alongside the leading order one. Our results suggest that a detailed, direct comparison is possible if all the model parameters are carefully tuned to match in the two different approaches.

Contents

| | | |
|----------|--|-----------|
| 1 | Introduction | 3 |
| 2 | Beam thrust spectrum for Higgs production | 4 |
| 2.1 | Beam thrust definition | 4 |
| 2.2 | The factorization theorem | 4 |
| 2.3 | Orders in perturbation theory and scale variations | 6 |
| 3 | Monte Carlo event generators | 7 |
| 3.1 | Resummation and matching | 7 |
| 3.2 | Parton showers in Herwig++ | 7 |
| 4 | Results | 8 |
| 4.1 | Framework setup | 8 |
| 4.2 | Standard shower | 8 |
| 4.3 | Dipole shower | 9 |
| 5 | Conclusions and outlook | 11 |

1 Introduction

The determination of the properties of the Higgs boson is one of the key aims of the LHC. Detailed theoretical predictions for the case of the Standard Model (SM) Higgs boson are especially important in light of the recent observation of a new boson with a mass of 125 GeV by the ATLAS and CMS collaborations [1, 2]. This discovery paves the way to precision determinations of Higgs production cross sections and decay rates, and at the same time opens the possibility for differential measurements.

Some of these measurements introduce a new characteristic scale in the process which, if significantly different from the scale of the hard process, gives rise to large logarithms. For example, this is the case for the Higgs transverse momentum distribution and for jet vetoed cross sections (see e.g. refs. [3] and [4]). In these two situations when the ratio of scales is significant the large Sudakov double logarithms that come along with the coupling constant must be taken into account to produce a sensible result. Resummed calculations are thus needed for a comparison with experimental measurements.

The resummation may be achieved in two different contexts. One possibility is to factorize the chosen observable into the convolution of a number of functions that describe different physics, evaluate each of these functions at its own scale where its logarithms are small, and evolve them up or down to a common scale by solving their Renormalization Group Equations (RGEs). Another approach is to exploit Monte Carlo parton showers, which are capable of reproducing the correct result by taking into account an arbitrarily large number of emissions.

A major ingredient needed to test the SM is the correct assessment of higher-order uncertainties for the outcomes of these two types of calculations. This is usually achieved in the analytical approach by varying some scales from which the fixed order result is manifestly independent up and down with a conventional factor. These variations effectively leave traces of higher-order corrections, allowing for an estimation of the size of the latter. In parton showers there are usually model parameters which can be exploited in a similar way.

A systematic attempt to compare the error bands that follow from these two approaches in the case of Higgs production processes at the LHC is missing in the literature, and constitutes the object of the present work. Namely we study the possibility of testing the resummation achieved by the parton shower against the analytical calculation. We provide preliminary results which scan the parton shower parameter space and may be used to get indications about the environment where a meaningful comparison could take place. The investigation is carried out with the multi-purpose event generator HERWIG++ [5] which provides the required flexibility. A comparison with different event generators is outside the scope of this work.

As a benchmark an observable for which high-order analytical resummed results are available is needed. This is the reason why we use the Higgs differential cross section in beam thrust and its cumulant. Beam thrust is defined in ref. [6] and the Higgs spectrum in this variable is resummed up to next-to-next-to-leading logarithms and correctly reproduces the next-to-next-to-leading fixed order result [4]; such a level of accuracy is sometimes indicated as NNLL+NNLO.

This report is structured as follows. In section 2 we briefly recall the definition and the main physical results for the considered observable. Section 3 contains a brief overview of the parton showers implemented in the chosen Monte Carlo event generator. In section 4 we present our results, and we conclude in section 5 with a few highlights and outlooks.

2 Beam thrust spectrum for Higgs production

2.1 Beam thrust definition

Beam thrust is an inclusive event shape variable which is well suited for carrying out logarithmic resummation. The appropriate version of beam thrust used in this work is the same as in ref. [4]: it is defined in the hadronic center-of-mass frame as

$$\mathcal{T}_{cm} \equiv \sum_k (E_k - |p_k^z|) , \quad (1)$$

where the index k runs over all particles in the event except for the daughters of the Higgs boson candidate. In the limit of massless final-state particles we also have

$$\mathcal{T}_{cm} = \sum_k |\vec{p}_{kT}| e^{-|\eta_k|} , \quad (2)$$

where \vec{p}_{kT} is the transverse momentum of the k -th particle and η_k is its rapidity, both with respect to the beam axis.

In order to understand the meaning of this variable, let us consider a generic particle in the final state. If the considered particle is soft, it has low \vec{p}_T and its contribution to beam thrust is small compared to the scale of the hard process. If it is hard but collinear with the beam, the absolute value of its rapidity is high and the relative addendum in the sum is exponentially suppressed. As only events with energetic, transverse particles have a significant beam thrust, \mathcal{T}_{cm} provides a continuous measure of the zero-jettiness of the event.

2.2 The factorization theorem

The cross section for Higgs production via gluon fusion, differential with respect to beam thrust, may be split into a singular and a nonsingular component

$$\frac{d\sigma}{d\mathcal{T}_{cm}} = \frac{d\sigma^s}{d\mathcal{T}_{cm}} + \frac{d\sigma^{\text{ns}}}{d\mathcal{T}_{cm}} \quad (3)$$

where the singular part scales as $\sim 1/\mathcal{T}_{cm}$ (modulo logarithms) for $\mathcal{T}_{cm} \rightarrow 0$ and is given by the factorization theorem

$$\begin{aligned} \frac{d\sigma^s}{d\mathcal{T}_{cm}} &= \sigma_0 H_{gg}(m_t, m_H, \mu) \int dY \int dt_a dt_b B_g(t_a, x_a, \mu) B_g(t_b, x_b, \mu) \\ &\quad \times S_{gg}^B \left(\mathcal{T}_{cm} - \frac{e^{-Y} t_a + e^Y t_b}{m_H}, \mu \right) . \end{aligned} \quad (4)$$

In this expression m_t is the mass of the top quark, Y is the rapidity of the Higgs boson, x_a and x_b are shorthands defined by

$$x_a = \frac{m_H}{E_{cm}} e^Y, \quad x_b = \frac{m_H}{E_{cm}} e^{-Y}, \quad (5)$$

and t_a and t_b correspond to the absolute values of the virtualities of the incoming gluons, which are however not measurable and therefore integrated over. In addition to the beam thrust distribution, we will consider the cumulant

$$\sigma(\mathcal{T}_{cm}^{\text{cut}}) \equiv \int_0^{\mathcal{T}_{cm}^{\text{cut}}} d\mathcal{T}_{cm} \frac{d\sigma}{d\mathcal{T}_{cm}}. \quad (6)$$

This represents the cross section for producing a Higgs boson in an event with $\mathcal{T}_{cm} < \mathcal{T}_{cm}^{\text{cut}}$ and carries the same information as the differential distribution.

This theorem is derived in Soft Collinear Effective Theory (SCET) [7, 8], where the hard modes of the particles above a certain scale μ_H are integrated out, and the remaining infrared divergencies are handled separately for the collinear and soft gluons. The functions that appear in (4) result from this procedure and are defined in SCET. The hard function H_{gg} describes the hard interaction between the incoming gluons, and being the square of Wilson coefficients of SCET operators may be computed perturbatively by matching QCD onto SCET. The beam functions B_g describe the initial state jets, collinear to the beam direction, which result from probing the incoming hadrons by requiring the event to have a specific value of \mathcal{T}_{cm} . In other words, the measurement of beam thrust probes each of the two protons before the interaction, and makes the PDFs unsuitable to parametrize the structure of the hadrons. For this purpose beam functions are needed instead, and these may be computed from PDFs according to the formula

$$B_g(t, x, \mu) = \sum_{j=q, \bar{q}, g} \int_x^1 \frac{d\xi}{\xi} \mathcal{I}_{gj} \left(t, \frac{x}{\xi}, \mu \right) f_j(\xi, \mu), \quad (7)$$

where the coefficients \mathcal{I}_{gj} can be computed in perturbation theory. Finally, the soft function S_{gg}^B describes the effect of soft radiation and contains both perturbative and nonperturbative physics.

Each of these three objects H_{gg} , B_g and S_{gg}^B is free from large logarithms at its own scale, which is a “hard” scale $|\mu_H| \sim m_H$ for the hard function, a “jet” or “beam” scale $\mu_B \sim \sqrt{m_H \mathcal{T}_{cm}}$ for the beam functions, and a “soft” scale $\mu_S \sim \mathcal{T}_{cm}$ for the soft function. The considered quantities satisfy a set of renormalization group equations whose solutions may be written in the form

$$\begin{aligned} H_{gg}(m_t, q^2, \mu) &= H_{gg}(m_t, q^2, \mu_H) U_H(q^2, \mu_H, \mu), \\ B_g(t, x, \mu) &= \int dt' B_g(t - t', x, \mu_B) U_B(t', \mu_B, \mu), \\ S_{gg}^B(k, \mu) &= \int dk' S_{gg}^B(k - k', \mu_S) U_S(k', \mu_S, \mu), \end{aligned} \quad (8)$$

where the U functions are evolution kernels that may be obtained by inserting the appropriate anomalous dimensions and explicitly solving the RGEs. The resummation of large logarithms is thus delegated to the evolution kernels.

Although the factorization theorem indicates a natural choice for the scales, there are additional boundary conditions. First, when $\mathcal{T}_{cm} < \Lambda_{QCD}$ nonperturbative effects become relevant and for this reason μ_S should never fall below this threshold. Second, in the region where the nonsingular cross section is important ($|\mu_H| \sim \mu_B \sim \mu_S \sim m_H$) important cancellations take place between the singular and nonsingular terms, and in order to make sure that this happens there should be not a single point but a whole region where all scales are set to the same value.

2.3 Orders in perturbation theory and scale variations

In order to discuss the order of the considered resummed results in perturbation theory, we observe that the Fourier transform of the cross section with respect to the dimensionless parameter $\tau \equiv \mathcal{T}_{cm}/m_H$ exponentiates and may be written as

$$\log \frac{d\sigma^s}{dv} \sim \log v (\alpha_s \log v)^n + (\alpha_s \log v)^n + \alpha_s (\alpha_s \log v)^n + \dots \quad (9)$$

where $v - i0$ is the Fourier-conjugate variable to τ and $n \geq 1$. The LL, NLL and NNLL results are defined as those expressions which include corrections respectively up to the first, second and third set of logarithms in this formula. Provided that the anomalous dimensions that enter in the equations for the evolution kernels are computed with a high enough number of loops and that the components of the singular calculation (hard, beam and soft functions) are available up to the required order, large logarithms may be correctly handled. Tough, in order to reproduce the correct cross section for large beam thrust fixed-order calculations must be considered. When the corrections in the resummed result are included at one higher order than what would be necessary for resummation only, we denote the result with an additional prime in the notation for logarithms defined before: indeed this already accounts for a part of the next set of large logs.

Once a result of a specific order is determined, we assess its theoretical uncertainty by exploiting its dependence on the scales μ_H , μ_B and μ_S . Indeed these parameters must drop out of the cross section order per order in perturbation theory, but a truncated series still shows a dependence on them that is a measure of higher order terms. The scale variations that are considered in [4] include an overall normalization shift up and down by a factor of 2, that accounts for the fixed order uncertainty at large beam thrust, and changes in the shape of the running beam and soft scales through the different regions of scale handling mentioned in section 2.2, which probe the size of single and double logarithms. The error bands from the last two variations are added in quadrature in more recent works [9].

3 Monte Carlo event generators

3.1 Resummation and matching

In Monte Carlo event generators the resummation of large logarithms is carried out through parton showers, which allow to take into account an arbitrary number of branchings. The chance of computing processes with many additional emissions relies on approximations that hold in the regions of phase space where the amplitudes for branchings diverge. Accounting for such events, which are neglected in fixed-order perturbation theory, sums up terms in which large logarithms from incomplete cancellation of divergencies compensate high powers of the coupling constant. This procedure may be used to enhance the results to formal LL accuracy.

Results obtained through parton showers may be improved including information from the fixed order calculations, both matching to NLO and merging with multiple jet tree level matrix elements. For the case of inclusive Higgs production we want to consider and compare two different approaches to NLO matching, namely MC@NLO [10] and POWHEG [11]. Although in its original formulation MC@NLO is conceived to work without the need of any change in the parton shower, its subtraction terms depend on the specific shower implementation. POWHEG, instead, is devised to be independent of the showering algorithm including the real emission matrix element inside a modified Sudakov form factor. It is particularly interesting to compare the outcomes of these two methods because the various contributions to the total theoretical uncertainty appear in different components of the calculation and are caught by different scale variations.

3.2 Parton showers in Herwig++

The standard parton shower algorithm implemented in HERWIG++ strives to reproduce soft gluon interference effects by considering angular ordered emissions. This is achieved by evolving the shower in the variable \tilde{q}^2 which is related to the angle between the branching products as described in [5]. It is possible to show that in the simple case of a single color dipole in the underlying hard process the shower algorithm, thanks to an appropriate treatment of the running coupling, effectively resums not only the leading logarithms, but also all NLL corrections.

Shortly after the MC@NLO approach had been devised, it was pointed out that matching in this scheme could be made much easier if the shower would follow closely the subtraction terms used to regularize soft and collinear divergencies in the NLO calculation. In order to exploit this observation and automate the NLO matching process, a different parton shower algorithm based on dipoles has been developed and implemented in HERWIG++, together with an additional module called MATCHBOX [12]. This component may be used to turn a NLO calculation into a matched calculation to be consistently combined with the shower. The coherent dipole shower approach is based on Catani-Seymour subtraction kernels [13], uses transverse momentum p_\perp^2 as an evolution variable to determine the ordering of the emissions and has been shown to properly include effects of soft gluon coherence [14].

4 Results

4.1 Framework setup

The physical context of the runs is set up as follows. The main goal being the comparison with [4], as a baseline we have run HERWIG++ without hadronization and without multiple partonic interactions. The environment of the run is defined by LHC running at 7 TeV in the scenario of a SM Higgs boson with a mass of 165 GeV. We do not consider the problem of Higgs reconstruction, and this makes the choice of setting the Higgs boson stable most convenient. In order to compute beam thrust the cleanest theoretical definition eq. (1) has been used, though in a real context summing over all particles is hardly possible because of pile-up and detector resolution. For the purpose of studying theoretical properties of cross sections, however, these effects are not relevant and the sum may be safely carried out, though a different definition of \mathcal{T}_{cm} where the index runs over jets is likely a necessary requirement for any experimental measurement of beam thrust. The starting scale of the parton shower is set at the value of the scale of the hard process (which is m_H at LO), and as a baseline we stop the radiation process at an infrared cutoff value of 2 GeV. The PDFs chosen for the simulations differ from the ones used in ref. [4] because the gluon distribution in the MSTW2008 NLO PDF set [15] goes negative in a relatively large x region for Q^2 close to the infrared cutoff, and this breaks down the standard probabilistic interpretation used to develop the shower. For this reason we rather use a similar but older PDF set which does not suffer from the mentioned problem, namely MRST2004 with evolution determined in the four-flavor FF scheme [16]. We will however provide an estimate of the impact of PDFs on our results at least in one specific case. For $\alpha_s(M_Z)$ we use the nominal value used in the chosen PDF fit for consistency. Ideally we always want to work with Monte Carlo samples which are large enough to guarantee that counting uncertainties in event ratios are small. One million events are generated in order to obtain each distribution; we have explicitly checked that statistical effects are much less relevant than theoretical uncertainties and for this reason we do not show the associated error bars on the plots.

4.2 Standard shower

The standard HERWIG++ parton shower is a well-consolidated tool in HEP process simulation, but it has the drawback of presenting the user with few predefined handles for changing parameters inside the algorithm. Without hacking the code, it is indeed possible to change only one scale, which is the argument of the coupling constant α_s used inside the shower. Doing so drives the partons to radiate more or less than expected without changing the overall normalization of the total cross section.

For inclusive Higgs production via gluon fusion $gg \rightarrow HX$ the LO matrix element is available along with a POWHEG NLO-matched one. The results we obtain with the settings discussed above are illustrated in figure 1. The NLO corrections to the considered process are known to be large; this can be seen in the plots where, apart from shape corrections, the LO cross section is a factor of about 2 lower with respect

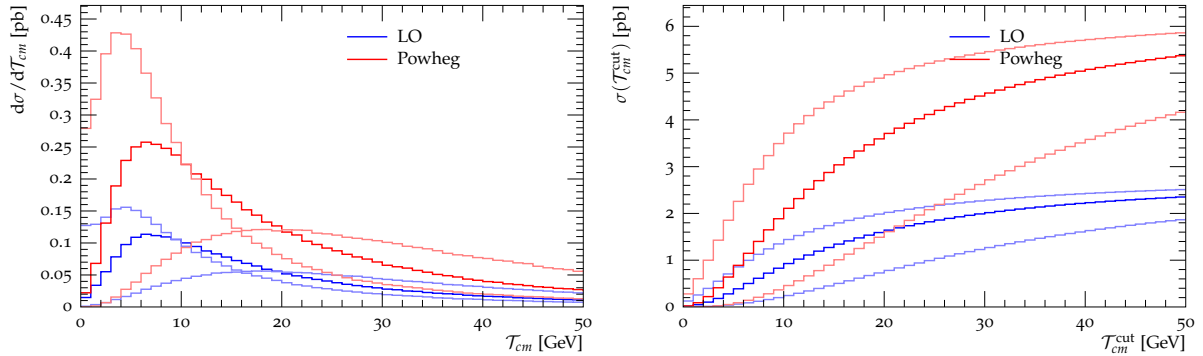


Figure 1: Beam thrust distribution (left) and cumulant (right) for inclusive Higgs production via gluon fusion at LHC 7 TeV, with $m_H = 165$ GeV. These results are obtained with the HERWIG++ standard shower. LO (blue) and NLO POWHEG (red) results are compared, along with their error bands (drawn in a lighter shade) determined with a variation of the argument of α_s in the shower by a factor of 2.

to the POWHEG result. The considered scale variation preserves the area under the distribution graphs as predicted, which also means that the lines in the cumulant plots converge to the same value for large τ_{cm} . We observe a significant shift of the peak for the beam thrust distribution when changing the amount of emitted radiation, along with a relevant change in the thickness of the tail.

In figure 2 we plot the beam thrust distribution for two different PDF sets, in order to get a feeling for the impact of the parton set choice. Namely, we compare the baseline MRST2004 set with the MSTW2008 set used for the analytical calculation in ref. [4], with the caveat that the second one suffers from the negative PDF issue mentioned above. Figure 2 shows that the effect of switching the parton set is approximately equivalent to a constant factor in the beam thrust distribution, and that the size of the change is approximately 10% for NLO and a little more for LO. An overall constant factor is the kind of effect expected from a variation of the coupling constant, and a quick comparison of orders of magnitude suggests that most of the variation is indeed due to the different α_s values the sets of PDFs are provided for.

4.3 Dipole shower

When running the dipole shower we switch off the intrinsic transverse momentum distribution of incoming hadrons. With this choice, in order to avoid overpopulation of the zero- τ_{cm} bin we reject events which did not radiate.

In the MATCHBOX component of HERWIG++, we have the possibility of making arbitrary changes of constant “scale” factors that multiply the squares of the following quantities:

- the scale at which the coupling constant α_s is evaluated during the shower (DRSF);
- the argument of the PDFs used in the dipole shower (DFSf);
- the scale of the strong coupling α_s in the hard matrix element (HRSF);

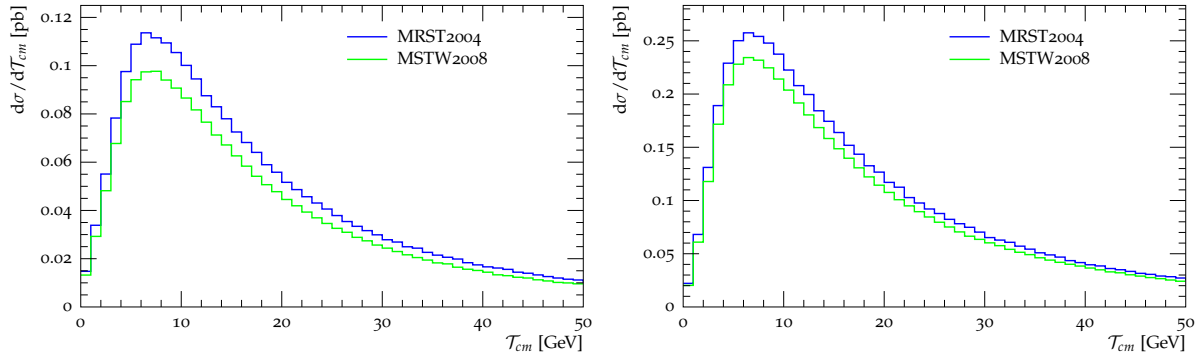


Figure 2: Comparison of the LO (left) and NLO POWHEG (right) beam thrust distributions obtained using the MRST2004 (blue line) and MSTW2008 (green line) PDF sets. The run settings are as in figure 1, and scale variations are not shown.

- the scale used for the PDFs in the hard process (HFSF);
- the starting scale for dipole shower evolution (DHSF).

The acronyms in brackets are quoted for easier identification of the plots and loosely refer to the name of the methods used to access them in the `HERWIG++` code.

One of the design targets of `MATCHBOX` is making the implementation of new NLO-matched processes easy: exploiting this feature allows us to include `MC@NLO` and `POWHEG` versions of the $gg \rightarrow HX$ matrix element among our results. Figure 3 summarizes the dipole shower results for the LO and the two different NLO-matched calculations, along with the bands obtained by varying the α_s evaluation scale in the radiation process. The dipole shower results show the general trend of peaking for smaller values of \mathcal{T}_{cm} compared to the ones for the standard shower.

In order to investigate this pattern and more generally the very low beam thrust region we consider two changes in the settings of the shower. First, we add the intrinsic transverse momentum model with `MATCHBOX` tunes; second, we shift the infrared cutoff of the shower. Once the intrinsic k_T of the partons is taken into account, in principle there is no longer any reason to discard non-radiating events as the delta function in the first bin is smeared out in the region with low beam thrust: therefore we include those events in the distributions. The effect of this choice is shown and compared to our baseline results in figure 4a, which suggests that the intrinsic k_T model might need to be tuned differently if we assume that the more well-established standard shower result is correct and the distribution should really drop as \mathcal{T}_{cm} goes to zero. The dependence on the p_\perp value for which the shower is stopped is illustrated in the simple case of LO in figure 4b. We observe a relevant difference between the two considered situations. For a future comparison with [4], it is important to note that the parameter which resembles an IR cutoff most in that work is τ_1 and that it stops the scale running at 5 GeV. It is possible that including hadronization in the Monte Carlo and nonperturbative models in the analytic approach may partly compensate the dependence on the limit where the perturbative regime is assumed to break down.

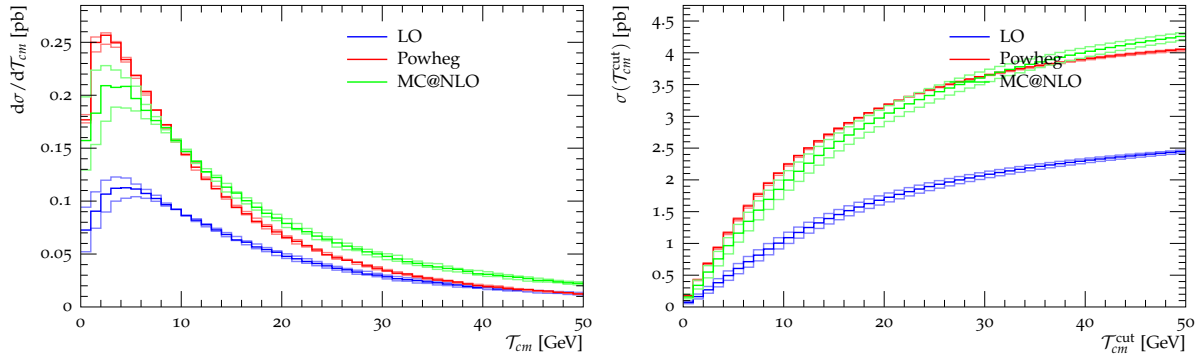


Figure 3: Beam thrust distribution (left) and cumulant (right) for inclusive Higgs production via gluon fusion at LHC 7 TeV with $m_H = 165$ GeV, using the dipole shower. LO (blue), POWHEG (red) and MC@NLO (green) results are compared, along with their error bands (drawn in a lighter shade) determined with a variation of the argument of α_s in the shower by a factor of $\sqrt{2}$.

The theoretical uncertainties of the quoted distributions are studied moving up and down each scale factor separately. In figure 5 we show the ratios of the curves with scale variations to the central prediction for the beam thrust cumulant cross section. The main contribution to the total uncertainty comes from changing α_s in the shower at low \mathcal{T}_{cm} and from moving up and down α_s in the hard matrix element in the high beam thrust region. Indeed this is expected because the first variation effectively changes the coefficients in front of the logarithms while the second is a plain rescaling of the cross section at LO and shows only little more structure at the following order. The impact of changing the scale argument of PDFs is small enough in the considered situations, while the starting scale of the shower has a rather large effect at LO. This can be understood observing that, while in NLO-matched computations the hard matrix element includes processes with Higgs plus one jet final states, at first order in perturbation theory the Higgs is the only hard object produced in the collision and it is up to the shower to handle extra emissions. The starting scale of the shower has then a sizeable impact on the region of phase space that will be populated by radiation at LO, as illustrated for the Higgs p_\perp spectrum in figure 6.

5 Conclusions and outlook

We have looked at the HERWIG++ outcomes for the beam thrust differential cross section and cumulant in Higgs production via gluon fusion, and compared runs with different settings to measure the size of the variations associated with different model parameters. We have changed the scale arguments of the coupling constant and of the PDFs by conventional factors and observed that they have a correspondance with the scale variations used to estimate theoretical uncertainties in analytic calculations. More precisely, with explicit reference to the results benchmarked in [4], we find that changing the argument of α_s in the hard process is similar to shifting the hard scale μ_H , and gives

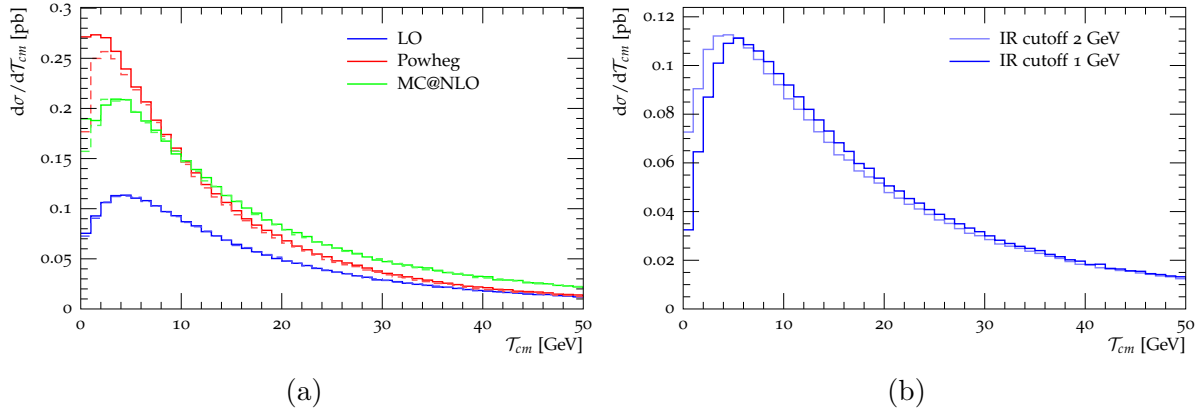


Figure 4: Effect of intrinsic k_T modeling (left) and infrared cutoff variation (right) on the event beam thrust distribution obtained with the dipole shower. In 4a the results with (solid lines) and without (dashed lines) intrinsic transverse momentum distribution are compared for all available orders and matching schemes. In 4b the LO beam thrust spectrum is compared for two different values of the infrared cutoff. Only central values without theoretical uncertainties are shown.

an estimate of the next fixed order term. The beam thrust distribution at low \mathcal{T}_{cm} is instead more sensitive to the argument of the coupling in the shower, whose variation is comparable to moving the beam and soft scales up and down; this is expected because it regulates the radiation in the shower, which resums the large logarithms.

Notwithstanding these promising observations, we do not attempt an exam of similarities and differences between our Monte Carlo predictions and results in the literature yet. Indeed this requires to understand the physics in the event generator at the level of being able to perfectly reproduce the conditions under which the analytic result has been derived.

Once such a level of comprehension is established and the Monte Carlo cross-validated against the RGE evolution and the factorization theorem, it will be interesting to study the influence of some effects which are accessible through event generators. These include multiple partonic interactions and hadronization: it is indeed not clear to which extent the factorization theorem in SCET accounts for them and, if so, in which component of the calculation they are included.

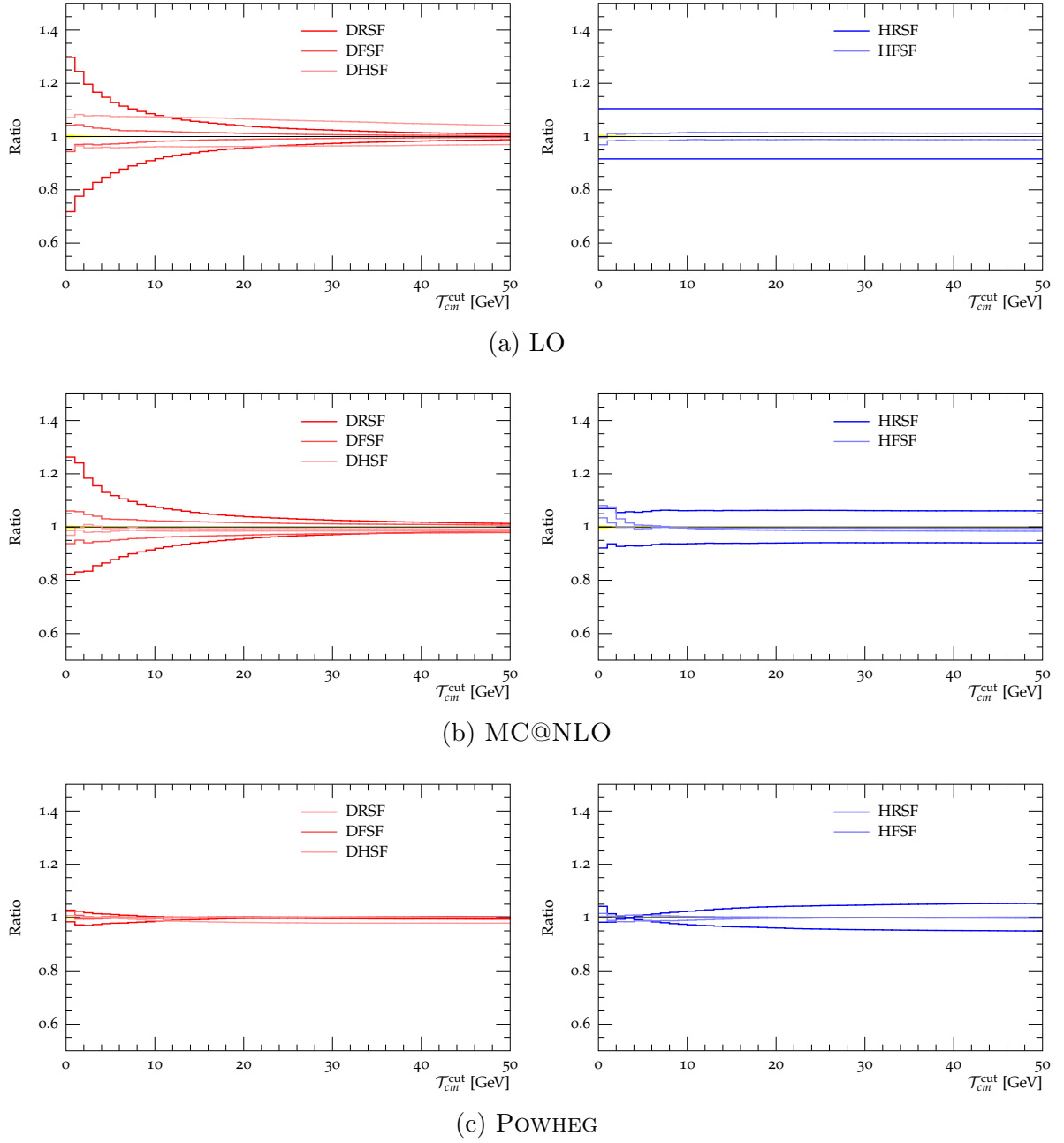


Figure 5: Ratios of the different single $\sqrt{2}$ scale factor variations to the central prediction for the beam thrust cumulant cross section. Results are presented for the dipole shower LHC 7 TeV, $m_H = 165$ GeV scenario without intrinsic transverse momentum modeling and rejecting events which did not radiate. The acronyms in the legends are explained in the text.

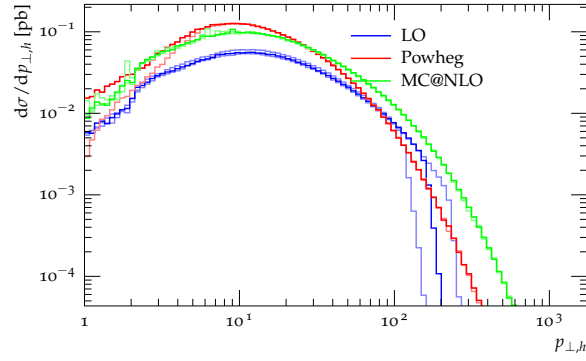


Figure 6: Double logarithmic plot of the Higgs transverse momentum distribution for LHC 7 TeV, $m_H = 165$ GeV obtained with the HERWIG++ dipole shower. LO (blue), POWHEG (red) and MC@NLO (green) results are shown, along with the results obtained changing the initial scale of the shower (light shade lines) by a factor of $\sqrt{2}$.

References

- [1] G. Aad *et al.*, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC,” *Phys.Lett.B*, 2012.
- [2] S. Chatrchyan *et al.*, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC,” *Phys.Lett.B*, 2012.
- [3] G. Bozzi, S. Catani, D. de Florian, and M. Grazzini, “The $q(T)$ spectrum of the Higgs boson at the LHC in QCD perturbation theory,” *Phys.Lett.*, vol. B564, pp. 65–72, 2003.
- [4] C. F. Berger, C. Marcantonini, I. W. Stewart, F. J. Tackmann, and W. J. Waalewijn, “Higgs Production with a Central Jet Veto at NNLL+NNLO,” *JHEP*, vol. 1104, p. 092, 2011.
- [5] M. Bahr, S. Gieseke, M. Gigg, D. Grellscheid, K. Hamilton, *et al.*, “Herwig++ Physics and Manual,” *Eur.Phys.J.*, vol. C58, pp. 639–707, 2008.
- [6] I. W. Stewart, F. J. Tackmann, and W. J. Waalewijn, “Factorization at the LHC: From PDFs to Initial State Jets,” *Phys.Rev.*, vol. D81, p. 094035, 2010.
- [7] C. W. Bauer, S. Fleming, D. Pirjol, and I. W. Stewart, “An Effective field theory for collinear and soft gluons: Heavy to light decays,” *Phys.Rev.*, vol. D63, p. 114020, 2001.
- [8] C. W. Bauer, D. Pirjol, and I. W. Stewart, “Soft collinear factorization in effective field theory,” *Phys.Rev.*, vol. D65, p. 054022, 2002.
- [9] I. W. Stewart and F. J. Tackmann, “Theory Uncertainties for Higgs and Other Searches Using Jet Bins,” *Phys.Rev.*, vol. D85, p. 034011, 2012.
- [10] S. Frixione and B. R. Webber, “Matching NLO QCD computations and parton shower simulations,” *JHEP*, vol. 0206, p. 029, 2002.
- [11] P. Nason, “A New method for combining NLO QCD with shower Monte Carlo algorithms,” *JHEP*, vol. 0411, p. 040, 2004.
- [12] S. Platzer and S. Gieseke, “Dipole Showers and Automated NLO Matching in Herwig++,” 2011.
- [13] S. Catani and M. Seymour, “A General algorithm for calculating jet cross-sections in NLO QCD,” *Nucl.Phys.*, vol. B485, pp. 291–419, 1997.
- [14] S. Platzer and S. Gieseke, “Coherent Parton Showers with Local Recoils,” *JHEP*, vol. 1101, p. 024, 2011.
- [15] A. Martin, W. Stirling, R. Thorne, and G. Watt, “Parton distributions for the LHC,” *Eur.Phys.J.*, vol. C63, pp. 189–285, 2009.

- [16] A. Martin, W. Stirling, and R. Thorne, “MRST partons generated in a fixed-flavor scheme,” *Phys.Lett.*, vol. B636, pp. 259–264, 2006.