Higher order QCD predictions for the Higgs p_T distribution

D. de Florian
Departamento de Física, FCEYN, Universidad de Buenos Aires, (1428) Pabellón 1 Ciudad Universitaria, Capital Federal, Argentina

G. Ferrera
Dipartimento di Fisica, Università di Milano and INFN, Sezione di Milano, I-20133 Milan, Italy

M. Grazzini [a]
Institut für Theoretische Physik, Universität Zürich, CH-8057 Zürich, Switzerland

D. Tommasini
University of Debrecen and Institute of Nuclear Research of the Hungarian Academy of Sciences, H-4001 Debrecen, Hungary

We consider Standard Model Higgs boson production through gluon–gluon fusion in hadron collisions. We combine the calculation of the next-to-next-to-leading order QCD corrections to the inclusive cross section with the resummation of multiple soft-gluon emissions at small transverse momenta up to next-to-next-to-leading logarithmic accuracy. We extend previous results including exactly all the perturbative terms up to order α_S^4 in our computation. We present numerical predictions for the Higgs boson spectrum at the LHC, together with an estimate of the corresponding uncertainties. We introduce the novel numerical program `HRes` that allows us to retain the full kinematics of the Higgs boson and of its decay products in the $H \to \gamma\gamma$, $H \to WW \to l\nu l\nu$ and $H \to ZZ \to 4l$ decay channels. We show explicit results in the $H \to \gamma\gamma$ decay mode, by using the nominal cuts applied in current Higgs boson searches by the ATLAS and CMS collaborations.

1 Introduction

One of the main tasks of the LHC program is the search for the Higgs boson [?] and the study of its properties (mass, couplings, decay widths). The experimental data already collected at the LHC in 2011 [?] considerably reduce the allowed mass range for the Standard Model (SM) Higgs boson H by essentially excluding the Higgs bosons in the mass range $\mathcal{O}(130$ GeV$) < m_H < \mathcal{O}(600$ GeV$)$, while observing an excess of Higgs boson candidate events around $m_H = 125$ GeV. More data from the ongoing LHC 2012 run, being operated at a centre-of-mass energy of 8 TeV, are needed to say whether these excesses really correspond to a Higgs signal or are just statistical fluctuations.

In this contribution we consider the production of the SM Higgs boson by the gluon fusion mechanism and its decays $H \to \gamma\gamma$, $H \to WW$ and $H \to ZZ$. The gluon fusion process $gg \to H$ [?], through a heavy-quark loop, is the main production mechanism of the SM Higgs boson at hadron colliders, and, as a consequence, it is crucial to achieve reliable theoretical predictions for

[a] On leave of absence from INFN, Sezione di Firenze, Sesto Fiorentino, Florence, Italy.

the cross section and the associated distributions. The dynamics of the gluon fusion mechanism is driven by strong interactions. Thus, accurate studies of the effect of QCD radiative corrections are mandatory to obtain precise theoretical predictions.

Here we consider the transverse momentum (p_T) spectrum of the SM Higgs boson produced by the gluon fusion mechanism. This observable is of direct importance in the experimental search. When studying the p_T distribution of the Higgs boson in QCD perturbation theory we define two different regions of p_T. In the large-p_T region ($p_T \sim m_H$), where the transverse momentum is of the order of the Higgs boson mass m_H, perturbative QCD calculations based on the truncation of the perturbative series at a fixed order in α_S are theoretically justified. In this region, the QCD radiative corrections are known up to $\mathcal{O}(\alpha_S^4)$, i.e., the next-to-leading order (NLO) [?,?,?] for the p_T spectrum and the next-to-next-to-leading-order (NNLO) as far as the inclusive cross section is considered. In the small-p_T region ($p_T \ll m_H$), the convergence of the fixed-order expansion is spoiled by the presence of large logarithmic terms, $\alpha_S^n \ln^m(m_H^2/p_T^2)$. To obtain reliable predictions, these logarithmically-enhanced terms have to be systematically resummed to all perturbative orders [?,?,?,?,?]. It is then important to consistently match the resummed and fixed-order calculations at intermediate values of p_T, in order to obtain accurate QCD predictions for the entire range of transverse momenta. In this contribution we present a selection of numerical results obtained by our group for the Higgs p_T spectrum [?] and discuss the effects of transverse-momentum resummation on the Higgs decay products [?].

2 The Higgs p_T spectrum

The numerical program HqT [?] implements the most accurate perturbative information that is available at present: soft-gluon resummation up to next-to-next-to-leading-logarithmic (NNLL) accuracy [?] combined with fixed-order perturbation theory up to $O(\alpha_S^4)$ in the large-p_T region [?]. The program is used by the Tevatron and LHC experimental collaborations to reweight the p_T spectrum of the Monte Carlo event generators used in the analysis and is thus of direct relevance in the Higgs boson search. The program HqT is based on the transverse-momentum resummation formalism described in Refs. [?,?,?], which is valid for a generic process in which a high-mass system of non strongly-interacting particles is produced in hadron–hadron collisions.

In Ref. [?] we performed some improvements with respect to the work of Ref. [?]. In particular, we have implemented the exact value of the NNLO hard-collinear coefficients $\mathcal{H}_N^{H(2)}$ computed in Ref. [?,?], and the recently derived value of the NNLL coefficient $A^{(3)}$ [?]. We have presented numerical results for Higgs production at the LHC and performed a study of the perturbative uncertainties. Our calculation for the p_T spectrum is implemented [?] in the updated version of the numerical code HqT, which can be downloaded from [?].

In Fig. **??**-left we consider Higgs boson production by gluon fusion at the LHC ($\sqrt{s} = 7$ TeV) and $m_H = 165$ GeV. We present our resummed results at NNLL+NLO accuracy, and we compare them with the NLL+LO results. The bands represent the scale uncertainty evaluated as explained in Ref. [?]. We find that the scale dependence at NNLL+NLO (NLL+LO) is about $\pm10\%$ ($\pm22\%$) at the peak, it decreases to about $\pm8\%$ ($\pm19\%$) in the region up to $p_T = 30$ GeV, and becomes $\pm10\%$ ($\pm18\%$) at $p_T = 60$ GeV. In the region beyond $p_T \sim 120$ GeV the resummed result looses predictivity, and its perturbative uncertainty becomes large. In Fig. **??**-right we compare the NLO and NNLL+NLO bands. At large values of p_T the NLO and NNLL+NLO scale uncertainty bands overlap, and the NLO result has smaller uncertainty. The new version of HqT implements a switching procedure, such that the fixed order NLO result is recovered at large p_T, where resummation is not any more relevant.

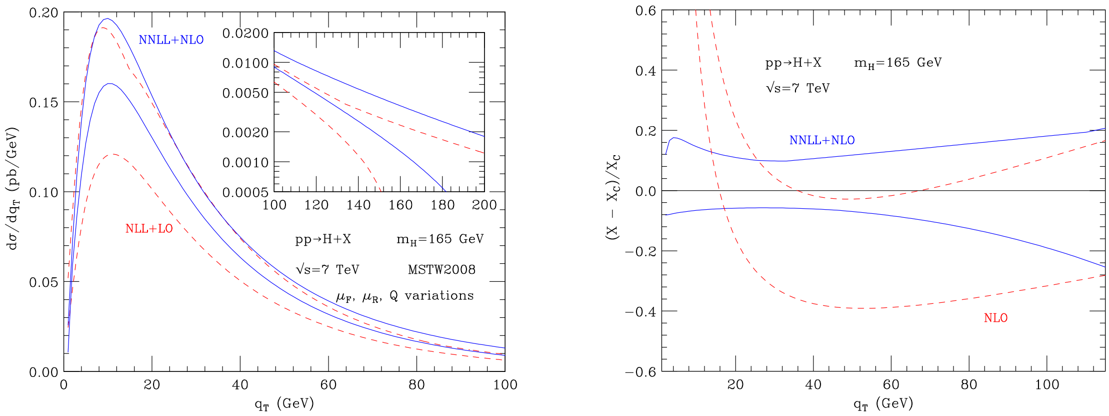

Figure 1: *The p_T spectrum of Higgs boson at the LHC: NNLL+NLO (solid) and NLL+LO (dashes) uncertainty bands (left panel); NNLL+NLO (solid) and NLO (dashes) uncertainty bands relative to the central NNLL+NLO result (right panel).*

3 Inclusion of Higgs boson decay products

In Ref.[?] we made a step forward with respect to previous work by including the Higgs boson decay products. We start from the doubly differential cross section, including transverse-momentum resummation and rapidity dependence[?] at full NNLL accuracy. We then include the Higgs boson decay and implement the ensuing result into an efficient Higgs event generator, that is able to simulate the full kinematics of the Higgs boson and of its decay products. This calculation is implemented in a new numerical program[?] called `HRes`, that embodies the features of `HNNLO`[?,?] and `HqT`. The decay modes that are implemented are $H \to \gamma\gamma$, $H \to WW \to l\nu l\nu$ and $H \to ZZ \to 4l$.

Here, we present just an example of the predictions that can be obtained with our program for Higgs boson production at the LHC ($\sqrt{s} = 8$ TeV) up to NNLL+NNLO accuracy. We focus on the $H \to \gamma\gamma$ decay channel and compare the resummed results with the corresponding fixed order results, obtained with the `HNNLO` numerical code. We consider the production of a SM Higgs boson with mass $m_H = 125$ GeV. We apply the following cuts on the photons. For each event, we classify the photon transverse momenta according to their minimum and maximum value, $p_{T\rm min}$ and $p_{T\rm max}$. The photons are required to be in the central rapidity region, $|\eta| < 2.5$, with $p_{T\rm min} > 25$ GeV and $p_{T\rm max} > 40$ GeV. A variable that is often studied is $\cos\theta^*$, where θ^* is the polar angle of one of the photons with respect to the beam axis in the Higgs boson rest frame. A cut on the photon transverse momentum p_T^γ implies a maximum value for $\cos\theta^*$ at LO. For example for $m_H = 125$ GeV and $p_T^\gamma \geq 40$ GeV we obtain $|\cos\theta^*| \leq |\cos\theta^*_{\rm cut}| \simeq 0.768$. At the NLO and NNLO the Higgs transverse momentum is non vanishing and events with $|\cos\theta^*| > |\cos\theta^*_{\rm cut}|$ are kinematically allowed. In the region of the kinematical boundary higher-order perturbative distributions suffer of logarithmic singularities. As expected[?], resummed results do not suffer of such instabilities in the vicinity of the LO kinematical boundary; the resummed distributions are smooth and the shape is rather stable when going from NLL+NLO to NNLL+NNLO. In Fig. **??** we report both the distributions (normalized to unity) obtained by fixed order and the resummed calculations. We see that the resummed results are smooth in the region around the kinematical boundary. Away from such region, fixed order and resummed results show perfect agreement.

The program `HRes` is built upon the fully exclusive calculation implemented in `HNNLO` and includes soft-gluon resummation at small transverse momenta of the Higgs boson. It thus provides a result which is everywhere as good as the NNLO result but much better in the small p_T region. These features should make our program a useful tool for Higgs searches and studies at the Tevatron and the LHC.

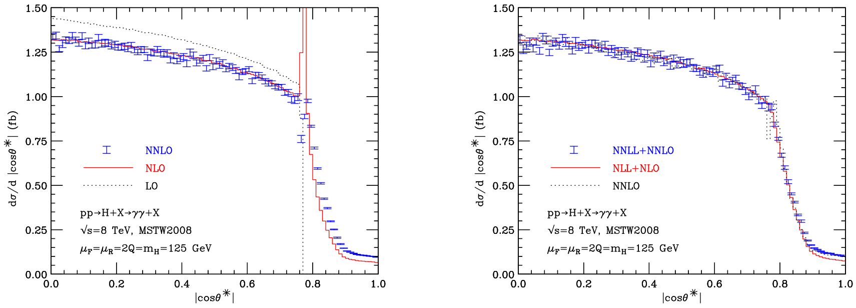

Figure 2: *Normalised* $\cos\theta^*$ *distribution at the LHC. On the left: LO, NLO and NNLO results. On the right: resummed predictions at NLL+NLO and NNLL+NNLO accuracy are compared with the NNLO result.*

References

1. F. Englert and R. Brout, Phys. Rev. Lett. **13** (1964) 321; P. W. Higgs, Phys. Lett. **12** (1964) 132, Phys. Rev. Lett. **13** (1964) 508.
2. G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **710** (2012) 49; S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **710** (2012) 26.
3. H. M. Georgi, S. L. Glashow, M. E. Machacek and D. V. Nanopoulos, Phys. Rev. Lett. **40** (1978) 692.
4. D. de Florian, M. Grazzini and Z. Kunszt, Phys. Rev. Lett. **82** (1999) 5209.
5. V. Ravindran, J. Smith and W. L. Van Neerven, Nucl. Phys. B **634** (2002) 247.
6. C. J. Glosser and C. R. Schmidt, JHEP **0212** (2002) 016.
7. Y. L. Dokshitzer, D. Diakonov and S. I. Troian, Phys. Lett. B **79** (1978) 269, Phys. Rep. **58** (1980) 269; G. Parisi and R. Petronzio, Nucl. Phys. B **154** (1979) 427; G. Curci, M. Greco and Y. Srivastava, Nucl. Phys. B **159** (1979) 451; J. C. Collins and D. E. Soper, Nucl. Phys. B **193** (1981) 381 [Erratum-ibid. B **213** (1983) 545]; J. C. Collins and D. E. Soper, Nucl. Phys. B **197** (1982) 446; J. C. Collins, D. E. Soper and G. Sterman, Nucl. Phys. B **250** (1985) 199; J. Kodaira and L. Trentadue, Phys. Lett. B **112** (1982) 66, report SLAC-PUB-2934 (1982), Phys. Lett. B **123** (1983) 335.
8. S. Catani, E. D'Emilio and L. Trentadue, Phys. Lett. B **211** (1988) 335.
9. S. Catani, D. de Florian and M. Grazzini, Nucl. Phys. B **596** (2001) 299.
10. G. Bozzi, S. Catani, D. de Florian and M. Grazzini, Nucl. Phys. B **737** (2006) 73.
11. S. Catani, M. Grazzini, Nucl. Phys. **B845** (2011) 297.
12. D. de Florian, G. Ferrera, M. Grazzini and D. Tommasini, JHEP **1111** (2011) 064.
13. D. de Florian, G. Ferrera, M. Grazzini and D. Tommasini, arXiv:1203.6321 [hep-ph].
14. D. de Florian and M. Grazzini, Phys. Rev. Lett. **85** (2000) 4678, Nucl. Phys. B **616** (2001) 247.
15. S. Catani and M. Grazzini, Phys. Rev. Lett. **98**, 222002 (2007).
16. S. Catani and M. Grazzini, arXiv:1106.4652 [hep-ph].
17. T. Becher and M. Neubert, Eur. Phys. J. C **71** (2011) 1665.
18. `http://theory.fi.infn.it/grazzini/codes.html`
19. G. Bozzi, S. Catani, D. de Florian and M. Grazzini, Nucl. Phys. B **791** (2008) 1.
20. M. Grazzini, JHEP **0802** (2008) 043 [arXiv:0801.3232 [hep-ph]].
21. S. Catani and B. R. Webber, JHEP **9710** (1997) 005.