Higher order QCD predictions for the Higgs $p_T$ spectrum

Massimiliano Grazzini*
University of Zurich

XLVIIth rencontres de Moriond, QCD and High Energy Interactions, march 11 2012

*On leave of absence from INFN, Sezione di Firenze
Outline

- Introduction
  - Fully differential calculations and HNNLO
- Transverse momentum spectrum and resummation
- HqT2.0
  - Results
- Merging HNNLO and HqT → HRes
  - New results for LHC at 8 TeV
- Summary and Outlook
Introduction

Gluon-gluon fusion is the dominant production channel of the Higgs boson at hadron colliders

Enormous activity in the last few years

Total cross section up to NNLO

R.Harlander, W.B. Kilgore (2002)
C. Anastasiou, K. Melnikov (2002)

EW corrections

U. Aglietti et al. (2004)
G. Degrassi, F. Maltoni (2004)
G. Passarino et al. (2008)

NNLO beyond large-$m_{\text{top}}$ approximation

R.Harlander et al. (2009, 2010)
M.Steinhauser et al. (2009)

QCD effects beyond NNLO

S. Catani, D. De Florian, P. Nason, MG (2003)

Mixed QCD-EW effects and EW from real radiation

C. Anastasiou et al. (2008)
C.Anastasiou et al. (2011)
Going differential

Total cross sections are ideal quantities: real experiment always have finite acceptances

In the case of gg→H two fully exclusive NNLO calculations are available

- FEHIP

  Based on sector decomposition:
  $H \rightarrow \gamma \gamma$, $H \rightarrow WW \rightarrow l\nu l\nu$

- HNNLO

  Based on subtraction method
  $H \rightarrow \gamma \gamma$, $H \rightarrow WW \rightarrow l\nu l\nu$, $H \rightarrow ZZ \rightarrow 4l$

  Public program that allows the user to apply arbitrary cuts and plot the corresponding distributions in the form of bin histograms

  C. Anastasiou, K. Melnikov, F. Petrello (2005)
  C. Anastasiou, G. Dissertori, F. Stoeckli (2007)
  S. Catani, MG (2007)
  MG (2008)

But fixed order calculation may develop perturbative instabilities when different kinematic scales are involved: typical example is Higgs $p_T$ spectrum
Transverse-momentum spectrum

Among the various distributions the transverse momentum spectrum plays an important role.

Its accurate knowledge helps to find strategies to improve statistical significance.

Transverse momentum ($p_T$) and rapidity ($y$) identify the Higgs kinematics.

The shape of rapidity distribution mainly determined by PDFs.

Effect of QCD radiation mainly encoded in the $p_T$ spectrum.

Moreover: the Higgs is a scalar production and decay processes essentially factorized.

When considering the transverse momentum spectrum it is important to distinguish two regions of transverse momenta.
To have $p_T \neq 0$ the Higgs boson has to recoil against at least one parton. The LO is of relative order $\alpha_S$.

NLO corrections are known.

Part of inclusive NNLO corrections

Large logarithmic corrections of the form $\alpha_S^n \ln^m(m_H/p_T)$ appear that originate from soft and collinear emission.

The perturbative expansion becomes not reliable.

LO: $\frac{d\sigma}{dq_T} \to +\infty$ as $p_T \to 0$

NLO: $\frac{d\sigma}{dq_T} \to -\infty$ as $p_T \to 0$

RESUMMATION NEEDED (effectively performed by standard MC generators)
Our formalism

S. Catani, D. de Florian, MG (2000)
G. Bozzi, S. Catani, D. de Florian, MG (2005)

Resummation must be performed in impact parameter b-space

We introduce some novel features:

\[
\frac{d\hat{\sigma}_{ac}^{(\text{res.})}}{dp_T^2} = \frac{1}{2} \int_0^\infty db b J_0(bp_T) W_{ac}(b, M, \hat{s}; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2)
\]

where the large logs are organized as:

\[
W_N^F(b, M; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2) = H_N^F(M, \alpha_S(\mu_R^2); M^2/\mu_R^2, M^2/\mu_F^2, M^2/Q^2)
\times \exp\{G_N(\alpha_S(\mu_R^2), L; M^2/\mu_R^2, M^2/Q^2)\}
\]

with

\[
L = \ln \frac{M^2 b^2}{b_0^2} \quad \tilde{L} = \ln \left(1 + \frac{Q^2 b^2}{b_0^2}\right)
\]

\[\text{and} \quad \alpha_S = \alpha_S(\mu_R)\]

- The form factor takes the same form as in threshold resummation
- Unitarity constraint enforces correct total cross section
- Allows a consistent study of perturbative uncertainties

G. Parisi, R. Petronzio (1978)
G. Curci, M. Greco, Y. Srivastava (1979)

PDFs factorized at $\mu_F \sim M = m_H$
The resummed and fixed order calculations can then be combined to achieve uniform theoretical accuracy over the entire range of $p_T$

\[
\frac{d\hat{\sigma}}{dp_T^2} = \frac{d\hat{\sigma}^{(\text{res.})}}{dp_T^2} + \frac{d\hat{\sigma}^{(\text{fin.})}}{dp_T^2}
\]

standard fixed order result minus expansion of resummed formula at the same order

The calculation can be done at:

- **NLL+LO**: we need the functions $g^{(1)}$, $g^{(2)}$ and the coefficient $\mathcal{H}^{(1)}_N$ plus the matching at relative order $\alpha_S$.

- **NNLL+NLO**: we also need the function $g^{(3)}$ and the coefficient $\mathcal{H}^{(2)}_N$ plus the matching at relative order $\alpha^2_S$.

*Note that here LO and NLO refer to the spectrum: they contribute to NLO and NNLO normalization!*

At NLL+LO the accuracy is roughly the same as in MC@NLO and POWEG.

NNLL+NLO represents the highest accuracy available to date.

Extensively used at the Tevatron and the LHC to correct (reweight) MC spectra.

Implemented in HqT.
Few improvements:

- The first version of HqT was based on a crude estimate of second order hard-collinear coefficient.

Consider only $\delta(1-z)$ term and fix its normalization using knowledge of total cross section. It works reasonably well both at the Tevatron and the LHC but now exact result for $\mathcal{H}_N^{(2)}$ is known and can be implemented.

- Exact treatment of resummation scale.

  - Makes possible more realistic studies of perturbative uncertainties.

- Value of $A^{(3)}$ for $q_T$ resummation implemented.

- Interface with LHAPDF.

Differences with first version at the percent level.
Scale uncertainty computed by independent variations of $\mu_F, \mu_R$ and $Q$ in the ranges $\frac{1}{2} m_H < \{\mu_F, \mu_R\} < 2m_H$ and $\frac{1}{4} m_H < Q < m_H$ with the constraints $\frac{1}{2} < \mu_F/\mu_R < 2$ and $\frac{1}{2} < Q/\mu_R < 2$

Perturbative uncertainty at NNLL+NLO ranges from about $\pm 10\%$ at the peak to about $\pm 8\%$ at $q_T=30$ GeV to $\pm 10\%$ at $q_T=60$ GeV
At large values of $q_T$ the resummed result loses predictivity: better to use NLO
NEW: HRes

We start from the NNLL prediction for $d\sigma/dp_Tdy$
(extension to rapidity does not lead to substantial complications)

We include Higgs decays $H \rightarrow \gamma\gamma$, $H \rightarrow WW \rightarrow l\nu l\nu$, $H \rightarrow ZZ \rightarrow 4l$

We then match the result with the fixed order computation implemented in HNNLO

We thus obtain a result which is everywhere as good as the NNLO result but includes the resummation of the large logarithmic terms at small transverse momenta

The calculation is implemented in a new numerical code name HRes that merges the features of HNNLO and HqT

HRes allows us to retain the full kinematical information on the Higgs boson and its decay products in $H \rightarrow \gamma\gamma$, $H \rightarrow WW \rightarrow l\nu l\nu$ and $H \rightarrow ZZ \rightarrow 4l$

The user can select the cuts and the required distributions

Price to pay: we must be inclusive over recoiling QCD radiation
Preliminary results: $H \rightarrow \gamma \gamma$

Selection cuts: $p_T^{\text{min}} > 25$ GeV, $p_T^{\text{max}} > 40$ GeV, $|\eta| < 2.5$

$\vartheta^*$ defined as the polar angle of one of the photons in the Higgs rest frame

At LO $|\cos \vartheta^*| = \sqrt{1 - \frac{4p_T^2}{m_H^2}}$. $\rightarrow$ Minimum $p_T$ implies $\cos \vartheta^*_{\text{max}} < 1$

NLO and NNLO develop perturbative instabilities

Resummed results are instead smooth around the boundary

S. Catani, B. Webber (1997)
Preliminary results: $H \rightarrow \gamma\gamma$

Define \( p_{Tt} = |\vec{p}_T^{\gamma_1} \times \hat{t}| \)

Where the thrust axis is

\[ \hat{t} = \frac{\vec{p}_T^{\gamma_1} - \vec{p}_T^{\gamma_2}}{|\vec{p}_T^{\gamma_1} - \vec{p}_T^{\gamma_2}|} \]

This variable has been used by ATLAS to divide the analysis in categories

In the Drell-Yan process it is called \( a_T \)

As for the \( p_T \) this distribution diverges when computed at fixed order

Resummed result behave as constant as \( p_{Tt} \rightarrow 0 \)

M. Vesterinen, T. Wyatt (2008)

A. Banfi et al. (2009)
Preliminary results: $H \rightarrow ZZ \rightarrow 4l$

Cuts: $p_T^{l_1} > 5$ GeV; $|\eta| < 2.5$; $m_1 > 50$ GeV; $m_2 > 12$ GeV

$m_1$ and $m_2$ are closest and next to closest to $m_z$ invariant masses

Resummation makes $p_T$ distributions harder

In the intermediate region effect is about +40% at NLL+NLO and +10% at NNLL+NNLO

At LO softest lepton $p_T>m_H/4$
hardest lepton $p_T>m_H/2$

Behaviour at the kinematical boundary is smooth $\rightarrow$ No instabilities beyond LO
Summary & Outlook

Among the various kinematical distributions in gg→H the $p_T$ spectrum plays an important role: embodies main effects of QCD radiation.

New improved version of HqT now available and being used in the experimental analyses: allows more realistic studies of TH uncertainties.

I have presented the new numerical program HRES that merges the features of HNNLO and HqT.

Higgs production at NNLO plus soft-gluon resummation at small $p_T$.

HRes allows us to retain the full kinematical information on the Higgs boson and its decay products in $H\rightarrow\gamma\gamma$, $H\rightarrowWW\rightarrowl\nu l\nu$ and $H\rightarrowZZ\rightarrow4l$.

Future possible improvements:

- Include heavy quark mass dependence up to NLL+NLO.
- Generate unweighted events.