QCD effects on Higgs Boson production and decay at Hadron colliders

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Outline

- Introduction
- Higgs boson production: transverse momentum distribution
- The inclusion of the Higgs boson decay: the new program HRes
- Results for $H \rightarrow \gamma\gamma$, $H \rightarrow WW \rightarrow l\nu l\nu$ and $H \rightarrow ZZ \rightarrow 4l$
- Summary
Higgs search at hadron colliders

- One of the most important production channel is the gluon-gluon fusion (largest cross section). Calculated up to NNLL+NNLO QCD & NLO EW

- In case of gluon-gluon fusion, the most useful channels are the electroweak decays (better ratio signal/background)
Gluon fusion total cross section calculation

- LO to NLO ~80-100% and no overlapping
- NLO to NNLO ~25% and overlapping

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

Further improvements (smaller corrections each):
- threshold resummation at the NNLL accuracy, EW corrections, mixed QCD-EW corrections, sub-leading terms in the 1/mt expansion, real effects from EW radiation

LHC $\sqrt{s} = 7$ TeV
From total cross section to differential distributions

- Total cross sections are ideal quantities (the detectors have finite acceptances) ➔ differential distributions are needed

- For Higgs boson production, the full kinematics is described by the rapidity \( y \) and the transverse momentum \( q_T \) or \( p_T \). Drell-Yan like process. See Simone Marzani's talk

- Only the decay products are observable. Interesting rapidity, transverse momentum, and also angular variables
In the limit $q_T \to 0$ the predictivity of the theory fails: at LO $d\sigma/dq_T$ diverges to $+\infty$ and at NLO there is an unphysical peak and then diverges to $-\infty$.

- The problem comes from *soft gluon emission*
Resummation: main idea

- The problem arises from the emission of one or more soft gluons, that gives terms enhanced by powers of $L \equiv \log(m_H^2/q_T^2)$

- If $q_T \sim m_H \rightarrow L \approx 0$

- If $q_T \ll m_H \rightarrow L \gg 1$

- If we resum the emission of soft gluons, we can reorganize the series:

\[
\sum_n \alpha_s^n \rightarrow \sum_{n,m} \alpha_s^n L^m
\]

- Note: we can introduce a new unphysical resummation scale $Q$ (with $Q \sim m_H$), analogous to the factorization and renormalization scales

\[
\log \left( \frac{M_H^2}{q_T^2} \right) = \log \left( \frac{M_H^2}{Q^2} \right) + \log \left( \frac{Q^2}{q_T^2} \right)
\]
This formalism has been implemented in a numerical code named $\text{HqT}$. The obtained distribution has no divergences in the limit $q_T \to 0$ and no unphysical peak.

At high $q_T$ we recover the f.o. results.

$\text{HqT}$ widely used by the experimental collaborations at the Tevatron and the LHC to correct (reweight) the $q_T$ distribution from MC event generators.
Upgrade from HqT to the new code HqT2.0

Limits of the previous version of HqT:

- Approximations in the NNLL predictions: the $H^{(2)}$ function was estimated by the unitarity constraint and the $A_3$ coefficient was assumed the same as the one in the threshold resummation.
- Resummation scale dependence not implemented; there is no way to estimate the resummation uncertainties.
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Upgrades:

- Now we know the exact form of the functions $H^{(2)}$ (Catani,Grazzini '11) and $A_3$ (Becher,Neubert '10) → we have computed the Mellin transform of the function $H^{(2)}$ and implemented it in the new version of the code → we obtain a slightly harder distribution (of the order ~1-2%).

- The resummation scale dependence is fully implemented → More reliable estimate of the theoretical uncertainties.

- Interface with LHAPDFs and compatibility with new Fortran compilers (practical advantages).
Numerical predictions of $HqT2.0$

- Central value: $\mu_R = \mu_F = 2Q = m_H$
- Scale variations: $m_H/2 \leq \{\mu_R, \mu_F, (2Q)\} \leq 2m_H$ and $\frac{1}{2} \leq \{\mu_R/\mu_F, \mu_R/Q\} \leq 2$
- At NNLL+NLO: in the peak region the theoretical uncertainty is of the order of 10%, at $\sim 100\text{GeV}$ about 20%
- High $q_T$: f.o. calculations (provided by the same code) give more reliable results.
Higgs decay

- The $q_T$ distribution of the Higgs boson is important, but it isn’t directly observable in the detectors; we can observe only the decay products.

- It is important to extend the computation to include the Higgs decay.
The new code **HRes**

D. de Florian, G. Ferrera, M. Grazzini, DT (to appear)

- We start from the NNLL prediction for $d\sigma/dp_T dy$; extension to rapidity does not lead to substantial theoretical complications - G. Bozzi, S. Catani, D. de Florian, M. Grazzini (2007)

- Despite the extension is theoretically straightforward, the efficient generation of Higgs like events according to the resummed double differential distribution and the inclusion of the decay require **substantial improvements** in the computational speed

- 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**
The new code **HRes**

- 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** can be obtained with the same run

- **Price to pay**: we must be inclusive over recoiling QCD radiation
Effect of cuts in photon distributions

- The real detectors have a finite acceptance. We consider a realistic example at LHC $\sqrt{s}=8\text{TeV}$, for the process $gg \rightarrow H + X \rightarrow 2 \gamma + X$

- For each event we classify the photon transverse momentum according to the minimum and maximum value: $(p_{T\text{min}}, p_{T\text{max}})$ and we study the relative distributions

- Cuts: $p_{T\text{min}} > 25\text{GeV}$, $p_{T\text{max}} > 40\text{GeV}$, $|\eta|<2.5$

<table>
<thead>
<tr>
<th>Cross section</th>
<th>LO</th>
<th>NLO</th>
<th>NLL+NLO</th>
<th>NNLO</th>
<th>NNLL+NNLO</th>
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<tr>
<td>Total [fb]</td>
<td>17.08</td>
<td>30.8</td>
<td>30.7</td>
<td>38.4</td>
<td>38.5</td>
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<tr>
<td>With cuts [fb]</td>
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<td>21.55</td>
<td>21.54</td>
<td>27.0</td>
<td>27.0</td>
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<tr>
<td>Efficiency %</td>
<td>65.3</td>
<td>70.0</td>
<td>70.3</td>
<td>70.2</td>
<td>70.2</td>
</tr>
</tbody>
</table>

- Effect of these cuts on the cross section: no substantial differences between resummed and f.o. predictions
Photon $p_{T_{\text{min}}}$ and $p_{T_{\text{max}}}$ distributions

- **LO**: kinematical boundary at $m_H/2$
- At NLO and NNLO: enhancement almost proportional to the rising total cross section; QCD radiation allows events beyond the kinematical limit
- Around the point of discontinuity at LO, there are instabilities at (N)NLO: Sudakow shoulder (Catani, Webber '98)
Photon $p_{T_{\text{min}}}$ and $p_{T_{\text{max}}}$ distributions

- The **resummed** distributions are smooth and the shape is rather stable, fixed order prediction recovered out from the unstability region
Predictions on the pTthrust distribution

\[ p_{Tt} = \left| \vec{p}_T^{\gamma\gamma} \times \hat{t} \right| \]

Where, the thrust versor \( \hat{t} \) and the transverse momentum of the \( \gamma\gamma \) diphoton system are defined as follows:

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

Same variable as \( a_\perp \) defined for the Drall-Yan process

The pTthrust variable is used by the ATLAS analysis to classify the events into categories.
$H \rightarrow WW \rightarrow ll\nu\nu$

- LHC $\sqrt{s}=8$TeV, $m_H=140$GeV

$gg \rightarrow WW + X \rightarrow ll\nu\nu + X$

- For each event we classify the lepton transverse momentum according to the minimum and maximum value: $(p_{Tmin}, p_{Tmax})$

- Cuts: lepton $p_T > 20$GeV & $|\eta|<2.5$, missing $p_T > 30$GeV, charged leptons invariant mass $> 12$GeV

- Resummation makes $p_T$ distributions harder, in the intermediate region effect is about +40% at NLL+NLO and +10% at NNLL+NNLO

- Behaviour at the kinematical boundary is smooth ➔ no instabilities beyond LO
$H \rightarrow ZZ \rightarrow 4l$

- LHC $\sqrt{s}=8\text{TeV}$, $m_H=150\text{GeV}$
- $m_1$ and $m_2$ are closest and next to closest to $m_z$ invariant masses
- **Cuts**: $p_{T_1} > 5 \text{ GeV}$; $|\eta| <2.5$; $m_1 > 50 \text{ GeV}$ $m_2 > 12 \text{ GeV}$
- At LO kinematical boundary:
  - softest lepton $p_T > m_H/4$
  - hardest lepton $p_T > m_H/2$
- As for the WW decay, resummation makes $p_T$ distributions harder; behaviour at the kinematical boundary is smooth $\implies$ no instabilities beyond LO
The year 2012 will be a crucial year for the SM Higgs boson. Wide region of Higgs boson masses already excluded, but still there is an excess of events in the mass region around 125 GeV. More data from LHC are needed, in order to clarify the nature of these excesses.

One of the most important Higgs boson observables is the transverse momentum distribution (embodies effects of initial state QCD radiation, its precise knowledge can help to setup strategies to improve statistical significance).

HQT is a numerical program that allows to compute the Higgs $p_T$ spectrum to the highest accuracy possible to date.

Upgrade of HQT: exact expression for $H^{(2)}$ and $A_3$ functions, full implementation on the resummation scale dependence, LHAPDFs interfacing and new compilers compatibility, studies of theoretical uncertainties.
Summary

- **New code **\texttt{HRes}: it merges the features of \texttt{HNNLO} and \texttt{HqT} to provide predictions everywhere as good as the NNLO predictions, but that include the resummation of the logarithmically enhanced terms at small transverse momentum.

- Predictions, including the \texttt{effects of cuts}, for the differential distributions: Higgs boson production up to NNLL+NNLO and decay in \texttt{two photons} and \texttt{WW/ZZ} to four leptons.

  Some typical pathologies of the fixed order predictions solved

- **Outlook**: predictions beyond the narrow width and large m-top approximations
Backup slides
Higgs boson production

The hard cross section is calculated as perturbative serie of $\alpha_s$ through fixed order calculations

- **LO** (production of H via ggH effective vertex)

- **NLO**; but **LO** if we consider the $q_T \neq 0$ region (at least one recoiling parton: $H+\text{jet}$)

- **NNLO**; but **NLO** if we consider the $q_T \neq 0$ region ($H+\text{jet(s)}$)
Resummation (2)

- We introduce the following decomposition of the partonic cross section

\[
\frac{d\sigma}{dq_T^2} = \frac{d\sigma^{(res)}}{dq_T^2} + \frac{d\sigma^{(fin)}}{dq_T^2}
\]

- The \((\text{res})\) term contains all the logarithmically enhanced contributions at small \(q_T\) and has to be computed by resumming them to all orders in \(\alpha_s\). These contributions can be organized in classes of terms (LL, NLL, NNLL...)

- The \((\text{fin})\) component is free of such contributions and can be evaluated by fixed order truncation of the perturbative series

- The resummed component gives the dominant contribution in the small \(q_T\) region, while the finite component dominates at large values of \(q_T\).

- The two components have to be consistently matched at intermediate values of \(q_T\).
Backup. Higgs production: rapidity distribution

- The rapidity distribution for the Higgs production is mainly driven by the PDFs of the incoming hadrons.
- Rather stable shape at various perturbative orders