Higgs boson production via gluon fusion in the POWHEG approach in the SM and in the MSSM

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Talk structure

$gg \rightarrow H$ in POWHEG

Consistency checks

Results

Conclusions

Future developments
Gluon fusion: current results

Most of the currently available codes use the effective theory in the $m_{\text{top}} \to \infty$ limit (HEFT).

\begin{itemize}
\item[(a)] LO
\begin{itemize}
\item[(b)] Real emission
\item[(c)] Virtual correction
\end{itemize}
\end{itemize}

Most important programs

\begin{itemize}
\item HQT - (NNLO+NNLL)-QCD (HEFT, no PS matching)
\item HNNLO - NNLO parton level MC (HEFT, no PS matching)
\item HRes NLO full, NNLO+NNLO-QCD HEFT (no PS matching)
\item HIGLU, Fehip - NLO full theory (but no PS matching)
\item iHixs - NLO full / NNLO HEFT (but no PS matching)
\item Pythia/Herwig - PS LO (HEFT)
\item MC@NLO/POWHEG - MC NLO + PS (HEFT)
\end{itemize}

The predictions of the HEFT are accurate enough?
Aims of our work

Implementation in the POWHEG framework of the gluon fusion process.
NLO-(QCD+EW) accuracy with exact masses dependence provided by already existing matrix elements:
SM (Aglietti et al, Bonciani et al)
MSSM (Bonciani et al, Degrassi e Slavich)

- Determination of the total cross section with the possibility of imposing realistic acceptance cuts.
- Study of the impact of mass effect on the distributions.
- Individuation and study of observables which allow to distinguish between SM and MSSM.
SM

Features

- Matrix elements expressed in terms of Harmonic PolyLogarithm (HPL).
- Full dependence from quarks mass, both for virtual and real contributions.
- Both NLO-QCD and NLO-EW corrections.
MSSM

Features

- Full dependence from quarks and squarks mass for the real emission diagrams.
- Virtual contributions from diagrams with quarks and gluons with full mass dependence.
- Virtual contributions from diagrams with quarks-squarks-gluinos in the light Higgs limit.
Consistency checks

- Agreement with the previous implementation in POWHEG in the $m_{\text{top}} \to \infty$ limit.
- Comparison with other programs for mutually calculable quantities with on-shell Higgs.
- SM: Total cross-section in agreement with hgvv (Vicini et al).
- SM: $p_T$ distributions in agreement with Fehipro.
- MSSM: Total cross section in agreement with Degrassi&Slavich code.
Results - $\sigma_H$ in the SM

Total inclusive cross-section.

Cross-section normalized to the one in the $m_{\text{top}} \to \infty$ limit.
Results - $d\sigma/dp_T^H$ in the SM for $m_H = 125$ GeV

- Quarks mass effect $O(15\%)$.
- Suppression at low $p_T$ due to the POWHEG Sudakov form factor.

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SM: bottom quark role

- The distribution with only the Top quark (exact) has a low $p_T$ a similar behavior to the one in the $m_{\text{top}} \rightarrow \infty$.
- Import bottom quark correction and suppression for small $p_T$.
- Effect of the same order of the NNLO-NNLL uncertainty band (most accurate evaluation available).
MSSM - Total cross section $\sigma_h$ - Light Higgs

- Ratio of the total cross section in the MSSM and in the SM, for equal $m_h$.
- $m_h^{\text{max}}$ scenario
- $\tan \beta - m_A$. plane scan.
- The ratio varies between 0.2 and 70.
- What is the role of the scalars?
- In the event of equal MSSM and SM cross-section, how can we distinguish the two models?
Role of the scalars in the MSSM

Ratio of the MSSM to the MSSM with only quarks cross-section.

Ratio of the MSSM only quarks to the SM cross-section.

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Study of the curve with equal cross-section

Ratio of the $p_T^h$ distribution in the MSSM and the one in the SM for equal Higgs mass.
Study of the curve with equal cross-section

Ratio of the $p_T^h$ distribution in the MSSM and the one in the SM for equal Higgs mass.
Study of the curve with equal cross-section

![Graph showing the ratio of the $p_T^H$ distribution in the MSSM and the one in the SM for equal Higgs mass.]

**POWHEG**

Ratio of the $p_T^H$ distribution in the MSSM and the one in the SM for equal Higgs mass.

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Ratio of the $p_T^H$ distribution in the MSSM and the on in the SM for equal Higgs mass.
Conclusions

- New implementation of the gluon fusion process in POWHEG: NLO-(QCD+EW) accuracy and full mass dependence for quarks and squarks.
- Bottom quark mass effect are not negligible.
- MSSM: non trivial role of quarks and squarks for total and differential cross-sections.
Future developments

Improvements

- Higgs decay.
- Phenomenological study in the SM/MSSM of the various decay channels in presence of acceptance cuts.
  - MSSM: $gg \rightarrow H$
  - MSSM: $gg \rightarrow A$.
  - MSSM: $b\bar{b} \rightarrow h$

Theoretical studies

- Analytical study of the specific behaviors observed in the numerical simulations.
Backup slides
Theoretical uncertainty of the cross section in $gg \to H$

$p_T^H$ spectrum with theoretical uncertainty bands.

Results from Grazzini et al.

Theoretical uncertainty bands relative to the central NNLO+NNLL value.
Mass effects and scale variation

\begin{align*}
\mu_{\text{fac}} &= m_H \\
\mu_{\text{ren}} &= m_H \\
\mu_{\text{fac}} &= \frac{m_H}{2} \\
\mu_{\text{ren}} &= \frac{m_H}{2} \\
\mu_{\text{fac}} &= 2 m_H \\
\mu_{\text{ren}} &= 2 m_H
\end{align*}

$p_T^h$ spectrum with theoretical uncertainty bands in the new POWHEG implementation

As expected the results are almost the same.

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\( p_T^H \) distribution - NLO vs NLO+PS

Different behavior for small \( p_T \).
The fixed order calculation is divergent while the NLO+PS result goes to zero.
Results - $d\sigma / dp_T^H$ in the SM for $m_H = 120$ GeV

Positive mass correction.
Results - $d\sigma / dp_T^H$ in the SM for $m_H = 120$ GeV

We have that:

$$\frac{R(t,b,\text{exact})}{B(t,b,\text{exact})} > \frac{R(t,\infty)}{B(t,\infty)}$$

from where:

$$\Delta(t,b,\text{exact}) < \Delta(t,\infty)$$
Results - $d\sigma / dp_T^H$ in the SM for $m_H = 500$ GeV

Negative mass correction.

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Results - $d\sigma / dp_T^H$ in the SM for $m_H = 500$ GeV

We have that:

$$\frac{R(t,b,\text{exact})}{B(t,b,\text{exact})} < \frac{R(t,\infty)}{B(t,\infty)}$$

from where:

$$\Delta(t,b,\text{exact}) > \Delta(t,\infty)$$
**EW corrections for $m_h = 120$ GeV**

Comparison between the $m_{\text{top}} \to \infty$ distribution and the one with full mass dependence and EW corrections.

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New results
New results

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POWHEG

P.O.W.H.E.G = POnitive Weight Hardest Emission Generator

The problem

► Matching of a NLO-QCD Monte Carlo (MC) event generator and Parton showers (PS) to achieve a better description of experimental data.
► Since a PS includes the Leading Log (LL) terms, it is necessary to develop a strategy to avoid double counting.

The solution

► POWHEG generates the hardest emission.
► The interface with the PS requires a $p_T$ ordered (or a $p_T$ vetoed shower).
► Independent from the specific PS implementation.
► Generates events with positive weight.
POWHEG: the generation of the events

The POWHEG formula for the generation of the event is:

\[
d\sigma = \bar{B}(\Phi_1)d\Phi_1 \left\{ \Delta(\Phi_1, p_{T}^{\text{min}}) + \Delta(\Phi_1, p_{T}) \frac{R(\Phi_1, \Phi_{\text{rad}})}{B(\Phi_1)} d\Phi_{\text{rad}} \right\} + \sum_q R_{q\bar{q}}(\Phi_1, \Phi_{\text{rad}})d\Phi_{\text{rad}}d\Phi_1
\]

\[
\bar{B}(\Phi_1) = B_{gg}(\Phi_1) + V_{gg}(\Phi_1) + \int d\Phi_{\text{rad}} \left\{ \hat{R}_{gg}(\Phi_1, \Phi_{\text{rad}}) + \sum_q \hat{R}_{gq}(\Phi_1, \Phi_{\text{rad}}) + \sum_q \hat{R}_{gq}(\Phi_1, \Phi_{\text{rad}}) \right\} + c.r.
\]

\[
\Delta(\Phi_1, p_{T}) = \exp \left\{ -\int d\Phi_{\text{rad}} \frac{R(\Phi_1, \Phi_{\text{rad}})}{B(\Phi_1)} \theta(k_{T} - p_{T}) \right\}
\]

- NLO normalization.
- Sudakov form factor with full matrix elements.
POWHEG: the generation of the events

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POWHEG: the generation of the events

- The POWHEG formula for the generation of the event is:

\[
d\sigma = \tilde{B}(\Phi_1) d\Phi_1 \left\{ \Delta(\Phi_1, p_{T}^{\text{min}}) + \Delta(\Phi_1, p_T) \frac{R(\Phi_1, \Phi_{\text{rad}})}{B(\Phi_1)} d\Phi_{\text{rad}} \right\} + \sum_q R_{q\bar{q}}(\Phi_1, \Phi_{\text{rad}}) d\Phi_{\text{rad}} d\Phi_1
\]

\[
\tilde{B}(\Phi_1) = B_{gg}(\Phi_1) + V_{gg}(\Phi_1) + \int d\Phi_{\text{rad}} \left\{ \hat{R}_{gg}(\Phi_1, \Phi_{\text{rad}}) + \sum_q \hat{R}_{qg}(\Phi_1, \Phi_{\text{rad}}) + \sum_q \hat{R}_{gq}(\Phi_1, \Phi_{\text{rad}}) \right\} + c.r.
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