**Study of NLO QCD and Electroweak Corrections to Higgs Boson Production in the Bottom Quark Fusion Process at the LHC**

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**Abstract**

Higgs boson production in bottom-quark fusion or in association with b quarks is an important testing ground for Beyond the Standard Model (BSM) physics at the CERN Large Hadron Collider (LHC). The theory predictions for these processes have to be under excellent theoretical control to be able to search for BSM couplings. We performed an analytical calculation of Next-to-Leading Order (NLO) corrections in Quantum Chromodynamics (QCD) to the bbH process. We compared our results with the ones of a state-of-the-art automated tool called GoSam and found agreement. After this validation step, we used GoSam to calculate the Electroweak (EW) corrections. As a final step, we are now implementing these calculations in a Monte Carlo simulation program to obtain realistic results for Higgs boson production in b-quark fusion, bh → H, at the LHC.

**Motivation**

The Standard Model (SM) Higgs boson has a weak Yukawa coupling to bottom quarks, which causes the relatively small cross section of Higgs production in association with b-quarks at the LHC.

![Figure 1: SM Higgs production cross sections at the LHC](image)

However, if we enhance the Yukawa coupling of bottom quarks, as it can be done for instance in a 2-Higgs Doublet Model (2HDM), bh → H could be the dominant process for Higgs boson production at the LHC. Precise predictions for this process are needed and require the inclusion of quantum-loop effects in QCD and EW theory (see, e.g., Refs.[1,2,3]).

![Figure 2: For large tan β, the dominant process of Higgs production is the one associated with b-quarks](image)

**Theory**

For the Drell-Yan process, q̄q → Z, when using the quark mass as regulator, the sum of vertex and self-energy corrections yields a UV finite result due to a Ward identity (a consequence of gauge invariance) [4,5]. However, if we have massless initial states of quarks, the quark self-energy contributions do not exist. Hence for this process, the virtual correction is only provided by the vertex correction to the Yukawa coupling and we need to renormalize the 1 Yukawa coupling to get rid of the UV divergence (we use dimensional regularization, D = 4 − ε) [3]:

\[
\delta M_Y = \frac{\alpha_Y^2}{16\pi^2} I_1(p) \tag{2}
\]

\[
I_1(p) = \int \frac{d^D k}{(2\pi)^D} e^{i k \cdot (p - q)} S(p) S(k) S(q - k) D(k) \tag{3}
\]

\[
M_Y = M_Y^{\text{bare}} D^{-1}(\epsilon)(1 - \frac{\epsilon}{4\pi} + \text{counterterm}) \tag{4}
\]

**Figure 5: NLO QCD vertex correction.**

- In order to get rid of the UV divergence, we need to add a counterterm to the Lagrangian:
  \[
  \delta \mathcal{L} = \delta \mathcal{L}_{\text{bare}} + \delta \mathcal{L} \tag{5}
  \]

And we can derive the Yukawa counterterm by using multiplicative renormalization constants, \(Y_\nu = (1 - \delta Y_\nu) Y_\nu\). By using the 375 renormalization scheme in QCD we find

\[
\delta Y_\nu = \frac{(1 + \epsilon)}{1 - \epsilon} \frac{\alpha_Y^2}{16\pi^2} \frac{1}{(1 - 2\epsilon)^{1/2}} \tag{6}
\]

Adding the resulting counterterm to the Lagrangian, we obtain UV finite matrix elements. However, we still have IR divergences which are cancelled by considering real gluon emission due to the KLV theorem.

![Figure 3: Tree-level diagram for bh → H production](image)

**Figure 6: Real gluon emissions for bh → H.**

Integrating over the whole phase space in \(d = 4 - \varepsilon\) dimensions yields cross section of the real gluon emission contribution:

\[
\sigma_{\text{bh} \rightarrow gH} = \frac{C_F a_T^2}{2 \pi} \left| M_{\text{tree}} \right|^2 \frac{1}{(1 - 2\epsilon)^{1/2}} \left| \frac{1}{\Gamma(1 - \epsilon)} + \mathcal{O}(\epsilon) \right| \tag{7}
\]

The Next-to-Leading Order (NLO) QCD calculation contains virtual one-loop and real corrections.

As we can see, if we add the real and the virtual corrections, we can cancel the soft divergence, but a collinear divergence is still remaining. This divergence is canceled when calculating the cross section for proton-proton collisions by convoluting with so-called parton distribution functions (PDFs).

- Thus, the hadronic cross section at NLO QCD for bh → H production reads:
  \[
  \sigma_{\text{NLO}} = \sigma_{\text{LO}} \times \sigma_{\text{pdf}} \tag{8}
  \]

The numerical calculation of \(\sigma_{\text{NLO}}\) is done by Monte Carlo integration programs (MCP).

**GoSam**

- GoSam [8,9] is a state-of-the-art automated tool for the calculation of one-loop QCD and EW amplitudes for multi-particle processes in renormalizable quantum field theories.

**Conclusions and Outlook**

- Higgs production in association with heavy quarks is highly related to new physics. In order to probe these couplings in Higgs production at the LHC, we need precision calculations of the production cross sections.
- GoSam is a powerful automated tool that can provide the virtual contributions at one-loop QCD and EW in a fully automated way. As I have shown (see also other comparisons in [9]), GoSam’s calculation is reliable at NLO QCD for the bh → H matrix element squared.
- The main objective of this project is to obtain QCD and EW NLO corrections by using GoSam for the complete process bh → ZZ and to interface GoSam to a Monte Carlo program (MCP) to obtain realistic predictions for the LHC.
- By applying the BLHA interface to our own MCP, we hope to eventually explore more exciting results, and compare our results with actual LHC data.

**References**


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**Table 1:** Comparison between GoSam and my analytic calculation