NLO QCD Predictions for Hadronic Higgs Production with Heavy Quarks

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in collaboration with

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1. The Search for the Higgs boson

The Higgs boson – a direct consequence of W and Z boson mass generation in the Standard Model (SM) via spontaneous symmetry breaking of the SU(2)\(_L\) \(\otimes\) U(1)\(_Y\) gauge group. Goldstone (1961); Goldstone, Salam and Weinberg (1962); Higgs (1964,1966); Kibble (1967); Brout and Englert (1964); Guralnik, Hagen and Kibble (1964)

The Higgs particle so far eluded direct observation.

We know from direct (LEP2) and indirect searches (EWK fits) that the SM Higgs boson mass lies in the range


\[114.4 \text{ GeV} < M_H \lesssim 237 \text{ GeV} \ (95 \% \ C.L.)\]

Both \(t\bar{t}h\) and \(b\bar{b}h\) production processes will play an important role in Higgs discovery (SM (LHC) and MSSM (LHC and Tevatron)) and in the measurements of Higgs properties, e.g. of the top quark Yukawa coupling at the LHC.
Dominant production modes: $gg \rightarrow H$ (background very large); $q\bar{q} \rightarrow WH, ZH$
(most promising for leptonic decay of $W/Z$)

State-of-the-art of QCD predictions for Higgs processes at hadron colliders:

<table>
<thead>
<tr>
<th>production process</th>
<th>$\sigma_{NLO,NNLO}$ by</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q\bar{q} \rightarrow (W, Z)H$</td>
<td>T.Han, S.Willenbrock, PLB 273 (1991)</td>
</tr>
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<td>$q\bar{q} \rightarrow q\bar{q}H$</td>
<td>T.Han, G.Valencia, S.Willenbrock, PRL 69 (1992); T.Figy, C.Oleari, D.Zeppenfeld, PRD 68 (2003) (distrib.)</td>
</tr>
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<td>$gg, q\bar{q} \rightarrow t\bar{t}H$</td>
<td>W.Beenakker et al., PRL 87 (2001), NPB 653 (2003); S.Dawson et al., PRL 87 (2001), PRD 65 (2002), PRD 68 (2003)</td>
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<td>$gg, q\bar{q} \rightarrow b\bar{b}H$</td>
<td>S.Dittmaier, M.Kramer, M.Spira, hep-ph/0309204 (2003); S.Dawson et al., PRD 69 (2004)</td>
</tr>
<tr>
<td>$gb(\bar{b}) \rightarrow b(\bar{b})H$</td>
<td>for a review see J.Campbell et al., Les Houches 2003 procs., hep-ph/0405302</td>
</tr>
<tr>
<td>$b\bar{b} \rightarrow H$</td>
<td>for a review see J.Campbell et al., Les Houches 2003 procs., hep-ph/0405302; R.Harlander, W.Kilgore, PRD 68 (2003) (NNL0)</td>
</tr>
</tbody>
</table>
\( \sigma_{NLO, NNLO} \) for Higgs production processes at hadron colliders:

(for references see previous slide)

from S. Dawson et al., hep-ph/0210109

\( t\bar{t}h: \mu \) varied between \( \mu_0 = m_t + M_h/2 \) and \( 2\mu_0 \).

from S. Dawson et al., in prep. (prelim.)

Many thanks to W. Kilgore and R. Harlander for providing their NNLO results.

D. Wackeroth, SUNY at Buffalo
Fermilab Theory Seminar
07/22/04
Dominant decay modes:

\[ M_H < 135 \text{ GeV}: \ H \rightarrow b\bar{b} \ \text{with} \ BR = 43\% , \]
\[ M_H > 135 \text{ GeV}: \ H \rightarrow W^+W^- \ \text{with} \ BR = 40\% \]

Branching ratios of the dominant SM Higgs decay modes (including QCD corrections):

from M.Carena and H.Haber, hep-ph/0208209
HDECAY (A.Djouadi et al.)
M.Spira, hep-ph/9810289
Tevatron SM Higgs discovery potential

Integrated luminosity per experiment for a 95% CL exclusion of a SM Higgs or a $3\sigma$ or a $5\sigma$ discovery:

Tevatron Higgs Sensitivity Study
FERMILAB-PUB-03/320E

based on $Z/WH$ production only,
$Z/W \rightarrow ll, l\nu, H \rightarrow b\bar{b}$

10% syst. uncertainty in S/B results in a
5,15,20 % increase in 95%CL, $3\sigma$, $5\sigma$
luminosity thresholds ($M_H = 120$ GeV)

Can $t\bar{t}H$ help?

SM Higgs discovery reach at the Tevatron Run II:

\[ M_H \lesssim 125 \text{ GeV} \] (95 % C.L. with 2 fb$^{-1}$, $3\sigma$ evidence with 5 fb$^{-1}$)

\[ M_H = 130 \text{ GeV} \text{ can be excluded with } 4 \text{ fb}^{-1} \]
In the Standard Model, Higgs boson production in association with $b$ quarks is suppressed by the small $b$ Yukawa coupling, $g_{bbH} = \frac{m_b}{v} \approx 0.02$.

In the MSSM, however, the cross sections to $p\bar{p}, pp \to b\bar{b}h$, $h = h^0, H^0, A^0$, are enhanced with respect to the SM for large values of $\tan \beta$:

$$g_{bb(h^0,H^0)}^{MSSM} = \frac{(-\sin \alpha, \cos \alpha)}{\cos \beta} g_{bbH} \quad \text{and} \quad g_{bbA^0}^{MSSM} = \tan \beta g_{bbH}$$

![Graphs showing cross-sections](from M.Carena, H.Haber, Prog.Part.Nucl.Phys.50 (2003)

M.Spira, Fortschr.Phys.46 (1998) and hep-ph/9810289 (update)
Search for MSSM $h = H^0, h^0, A^0$ in 3 $b$-tagged events using D0 Run II data (left) and Tevatron 95 % CL exclusion contours for $b\bar{b}h \to b\bar{b}b\bar{b}$ (right):

from The D0 collaboration, D0 Note 4366 - CONF
see also talk by S.M. Wang, Moriond 2004
see also talk by A. Melnitchouk, Pheno 2004

LHC SM Higgs discovery potential

\[ \int L \, dt = 30 \text{ fb}^{-1} \]
(no K-factors)

ATLAS

\[ H \rightarrow \gamma \gamma \]
\[ t\bar{t}H (H \rightarrow bb) \]
\[ H \rightarrow ZZ(\ast) \rightarrow 4l \]
\[ H \rightarrow WW(\ast) \rightarrow l\nu l\nu \]
\[ qqH \rightarrow qq WW(\ast) \]
\[ qqH \rightarrow qq \tau\tau \]

Total significance

from S. Gentile
ATL-PHYS-2004-009 (and references therein)

For \( M_H < 130 \text{ GeV} \) the SM Higgs search

is mainly through \( t\bar{t}H \).
The LHC sensitivity for a MSSM $h^0$ boson discovery (left) and the discovery potential for $b\bar{b}h^0$ with $h^0 \rightarrow \mu^+\mu^-$ (right) (5σ curves):

$$g_{bbh^0}^{MSSM} = \frac{-\sin\alpha}{\cos\beta} g_{bbH}^{MSSM} \text{ and } g_{tth^0}^{MSSM} = \frac{\cos\alpha}{\sin\beta} g_{ttH}^{MSSM}$$

![Diagram showing LHC sensitivity and discovery potential for MSSM particles](image)

from S.Gentile, ATL-PHYS-2004-009 (and references therein)
The LHC sensitivity for MSSM Higgs boson discoveries (5σ curves):

from S. Gentile, ATL-PHYS-2004-009 (and references therein)
Expected relative error on the determination of $\sigma_{\text{Higgs}}$ at the LHC:

$t\bar{t}h$ directly probes the top quark Yukawa coupling:

at the LHC with 200 fb$^{-1}$ and $M_H \lesssim 130$ GeV $g_{ttH}$ can be measured with a precision of 15-20%.

from D.Zeppenfeld, hep-ph/0203123 (and references therein)
Need for NLO QCD calculations

- LO calculations have very strong renormalization/factorization scale dependence:

\[ \sigma(p\bar{p} \to b\bar{b}h) \text{ [fb]} \]

Tevatron, \( \sqrt{s} = 1.96\text{TeV}, M_h = 120\text{GeV} \)

- \( \mathcal{O}(\alpha_s) \) corrections can strongly increase/decrease the total production rate.

- \( \mathcal{O}(\alpha_s) \) corrections may affect the shape of distributions.
2. Associated $t\bar{t}$ Higgs production at hadron colliders

$t\bar{t}H$ production at the Tevatron $p\bar{p}$ collider is dominated by the $q\bar{q}$ initiated process ($>95\%$ of $\sigma_{LO}$ at 2 TeV):

\[ \begin{align*}
& \text{production at the LHC } pp \text{ collider is dominated by the } gg \text{ initiated process} \\
& (\text{but all other production processes should be taken into account too)}:\n\end{align*} \]
\(O(\alpha_s)\) corrections to \(p\bar{p}, pp \to t\bar{t}H\) production: Some technical details


At NLO QCD the cross section includes virtual and real gluon radiation:

Examples of real and virtual \(O(\alpha_s)\) corrections to \(p\bar{p} \to t\bar{t}H\)
Examples of real and virtual $\mathcal{O}(\alpha_s)$ corrections to $pp \rightarrow t\bar{t}H$

The calculations of the $\mathcal{O}(\alpha_s)$ corrections to $gg \rightarrow t\bar{t}H$ and $q\bar{q} \rightarrow t\bar{t}H$ are technically similar.

However, in the case of $gg \rightarrow t\bar{t}H$ there are new challenges, e.g., spurious singularities arising in the reduction of pentagon tensor integrals.
NLO QCD total inclusive cross section to $p\bar{p}, pp \to t\bar{t}H$:

$$\sigma_{NLO} = \sum_{ij=q\bar{q}, gg, qg} \frac{1}{1 + \delta_{ij}} \int dx_1 dx_2 [\mathcal{F}_i^p(x_1, \mu)\mathcal{F}_j^\bar{p}(x_2, \mu)\hat{\sigma}_{NLO}^{ij}(x_1, x_2, \mu) + (1 \leftrightarrow 2)]$$

with the parton level cross sections

$$\hat{\sigma}_{NLO}^{ij} = \hat{\sigma}_{LO}^{ij} + \frac{\alpha_s}{4\pi} \delta\hat{\sigma}_{NLO}^{ij} \text{ with } \delta\hat{\sigma}_{NLO}^{ij} = \hat{\sigma}_{\text{virt}}^{ij} + \hat{\sigma}_{\text{real}}^{ij}$$

\(\hat{\sigma}_{\text{virt}}^{ij}\):
- **UV divergences**: renormalized in \(d = 4 - 2\epsilon\) dimensions by suitable set of counterterms (modified \(MS\) scheme, on-shell subtraction for top)

\(\hat{\sigma}_{\text{real}}^{ij}\):
- **IR divergences**: regularized in \(d = 4 - 2\epsilon\) dimensions \(\Rightarrow\) soft and collinear singularities appear as poles in \(\frac{1}{\epsilon^2}, \frac{1}{\epsilon}\). IR singularities are completely canceled by corresponding IR poles in

**IR divergences**: extracted by suitable cuts on gluon phase space (phase space slicing): two and one cut-off PSS method using crossing symmetry and color ordered amplitudes. Remaining initial-state IR singularities are absorbed in PDFs (mass factorization).
Phase Space Slicing: isolate the region of the $t\bar{t}H + g$ phase space where

$$s_{ig} = 2p_i \cdot p_g = 2E_i E_g (1 - \beta_i \cos \theta_{ig}) \to 0$$

by introducing suitable cutoff parameters.

two cut-off PSS method: $\delta_s, \delta_c$

e.g. Bergman, Baer, Ohnemus, Owens, Reno, ..., for a review see B.Harris, J.Owens, PRD 65 (2002)

$$E_g < \delta_s \sqrt{s}/2 \ , \ (1 - \cos \theta_{ig}) < \delta_c$$

one cut-off PSS method: $s_{\text{min}}$

Giele, Glover, and Kosower; Keller and Laenen

$$s_{ig} < s_{\text{min}}$$

and compute $\hat{\sigma}_{\text{real}}^{ij}$

- analytically below the cut-off(s)

Together with $\hat{\sigma}_{\text{virt}}^{ij}$ this constitutes the weight with $2 \rightarrow 3$ kinematics.

- numerically above the cut-off(s) $\Rightarrow$ weight with $2 \rightarrow 4$ kinematics.
Phase Space Slicing with two cut-offs

e.g. Bergman, Baer, Ohnemus, Owens, Reno, ..., for a review see B.Harris, J.Owens, PRD 65 (2002)

\[ \hat{\sigma}_{real}^{ij}(ij \rightarrow t\bar{t}H + g) = \hat{\sigma}_{soft}(E_g < \frac{s}{2} \delta_s) + \hat{\sigma}_{hard}(E_g > \frac{s}{2} \delta_s) \]

In the soft limit \((E_g \rightarrow 0)\):

\[ d(PS_4) \xrightarrow{soft} d(PS_3)d(PS_g) = d(PS_3) \frac{d^{d-1}k^c}{(2\pi)^{d-2}E_g} \]

\[ |A_{\text{real}}(ij \rightarrow t\bar{t}h + g)|^2 \xrightarrow{soft} (4\pi\alpha_s)|A_{LO}|^2 \Phi_{eik} \]

where the eikonal factor \(\Phi_{eik}\) contains the soft poles

\[ \Phi_{eik} \propto \sum_{ij} \left( \frac{s_{ij}}{s_{ig}s_{jg}} - \frac{m_i^2}{s_{ig}^2} - \frac{m_j^2}{s_{jg}^2} \right) \]

\[ \hat{\sigma}_{soft} = \int d(PS_3)|A_{LO}|^2 \int d(PS_g) \Phi_{eik} \]

Analytical integration in \(d = 4 - 2\epsilon\) dimensions yields IR divergences as poles in \(\epsilon \rightarrow 0\):

\[ \hat{\sigma}_{soft} \propto \frac{1}{\epsilon}, \frac{1}{\epsilon^2} \]
moreover

\[ \hat{\sigma}_{hard} = \hat{\sigma}_{coll}((1 - \cos \theta_{tg}) < \delta_c) + \hat{\sigma}_{non-coll}((1 - \cos \theta_{tg}) > \delta_c) \]

In the collinear limit \((i \rightarrow i'g, p_i' = zp_i, p_g = (1 - z)p_i)\)

\[
d(PS_4)(ij \rightarrow t\bar{t}h + g) \xrightarrow{\text{collinear}} d(PS_3)(i'j \rightarrow t\bar{t}h)zd(PS_g) \]

\[
|A_{real}(ij \rightarrow t\bar{t}h + g)|^2 \xrightarrow{\text{collinear}} |A_{LO}|^2(4\pi\alpha_s)\frac{2P_{ii'}(z)}{z\,s_{ig}}
\]

\((P_{ii'}: \text{AP-splitting function})\)

\[
\hat{\sigma}_{coll} \propto \int d(PS_3)|A_{LO}|^2 \int d(PS_g)\sum_i \frac{P_{ii'}}{s_{ig}}
\]

Analytical integration in \(d = 4 - 2\epsilon\) dimensions yields collinear IR divergences as pole in \(\epsilon \rightarrow 0: \hat{\sigma}_{coll} \propto \frac{1}{\epsilon}\)

The remaining real hard part

\[
\hat{\sigma}_{non-coll} = \int d(PS_4)_{non-coll}|A_{real}(q\bar{q} \rightarrow t\bar{t}h + g)|^2
\]

is computed numerically.
Phase Space Slicing with one cut-off

Giele, Glover, and Kosower; Keller and Laenen

- Cross all partons to final state:

  \[ q\bar{q} \rightarrow t\bar{t}h(+g) \]  

  becomes  

  \[ h \rightarrow q\bar{q}t\bar{t}(+g) \]  

  (same for gg initial state)

- Reduce \( \delta_{q\bar{q}t\bar{t}h}^{real} \) to color ordered amplitudes using

  \[
  T_{c_1c_2}^a T_{c_3c_4}^a = \frac{1}{2} \left( \delta_{c_1c_4} \delta_{c_3c_2} - \frac{1}{N} \delta_{c_1c_2} \delta_{c_3c_4} \right)
  \]

  so that

  \[
  |A_{real}|^2 \propto \left\{ \frac{N}{2} \left[ |B_1|^2 + |B_2|^2 \right] + \frac{1}{2N} \left[ -2|B_3 + B_4|^2 + |B_3|^2 + |B_4|^2 \right] \right\}
  \]
• Introduce a cut-off parameter $s_{min}$; the radiated gluon is considered soft/collinear if $s_{ig} < s_{min}$.

Use color ordered amplitudes to systematically factor out soft/collinear divergences.

• Cross $q\bar{q}$ to initial state, $H$ to final state:
  • interchange $q$ and $\bar{q}$ accordingly
  • add crossing function:

$$\hat{\sigma}_{tot}^{q\bar{q}} = \hat{\sigma}_{soft} + \hat{\sigma}_{coll} + \hat{\sigma}_{\text{crossing}} + \hat{\sigma}_{\text{non-coll}}$$

Final steps

• Add virtual $\mathcal{O}(\alpha_s)$ corrections $\Rightarrow$ IR divergences in $\hat{\sigma}_{virtual}$ are canceled by corresponding divergences in $\hat{\sigma}_{soft} + \hat{\sigma}_{coll} (+\hat{\sigma}_{\text{crossing}})$.

• Mass factorization
  When convoluting $\hat{\sigma}_{q\bar{q}}^{NLO}$ with the PDFs the remaining initial-state IR singularities are absorbed into the PDFs.
Cancellation of cut-off dependences in $\sigma_{\text{NLO}}$


Tevatron

LHC

D.Wackeroth, SUNY at Buffalo
Fermilab Theory Seminar
07/22/04
$s_{\text{min}}$ dependence cancels in $\sigma_{\text{NLO}}$

**Tevatron**

![Graph showing $\sigma_{\text{NLO}}$ and $\sigma_{\text{crossing}}$ versus $s_{\text{min}}$ (GeV$^2$)]

**LHC**

![Graph showing $\sigma_{\text{NLO}}$, $\sigma_{\text{gg}}$, and $\sigma_{\text{real}}$ versus $s_{\text{min}}$ (GeV$^2$)]

Main Result

Drastically reduced scale dependence of the total inclusive production cross sections:

\[ p\bar{p} \rightarrow t\bar{t}H X \text{ at the Tevatron} \]

\[
\begin{array}{c|cc}
\mu & \sigma_{LO} \text{ (fb)} & \sigma_{NLO} \text{ (fb)} \\
\hline
m_t & 6.866(1) & 4.86(3) \\
m_t + M_h/2 & 5.909(1) & 4.85(2) \\
2m_t & 4.879(1) & 4.69(2) \\
2m_t + M_h & 4.255(1) & 4.51(2) \\
\end{array}
\]


see also W. Beenakker et al., PRL 87 (2001), NPB 653 (2003)
Main Result

Drastically reduced scale dependence of the total inclusive production cross sections:

\[ pp \rightarrow t\bar{t}H X \] at the LHC

\[ \sqrt{s} = 14 \text{ TeV} \]
\[ M_h = 120 \text{ GeV} \]
\[ \mu_0 = m_t + M_h / 2 \]

CTEQ5 PDF's

<table>
<thead>
<tr>
<th>( \mu )</th>
<th>( \sigma_{LO} ) (fb)</th>
<th>( \mu/\mu_0 )</th>
<th>( \sigma_{NLO} ) (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_t )</td>
<td>582.92(6)</td>
<td></td>
<td>719(4)</td>
</tr>
<tr>
<td>( m_t + M_h / 2 )</td>
<td>520.47(6)</td>
<td></td>
<td>697(3)</td>
</tr>
<tr>
<td>( 2m_t )</td>
<td>450.09(5)</td>
<td></td>
<td>663(3)</td>
</tr>
<tr>
<td>( 2m_t + M_h )</td>
<td>405.54(4)</td>
<td></td>
<td>634(2)</td>
</tr>
</tbody>
</table>

from S.Dawson, L.H.Orr, L.Reina, DW, PRD 67 (2003),
see also WBeenakker et al., PRL 87 (2001), NPB 653 (2003)
$M_H$ dependence

$pp \rightarrow t\bar{t}H X$ at the LHC

$\sqrt{s}=14$ TeV
CTEQ5 PDF’s

$\sigma_{LO}, \mu=\mu_0$
$\sigma_{NLO}, \mu=\mu_0$
$\sigma_{LO}, \mu=2\mu_0$
$\sigma_{NLO}, \mu=2\mu_0$

$\mu_0=m_t+M_H/2$

$p\bar{p} \rightarrow t\bar{t}H X$ at the Tevatron

$\sqrt{s_H}=2$ TeV


see also W BEENAKKER et al., PRL 87 (2001), NPB 653 (2003)
Summary for $t\bar{t}h$

- $t\bar{t}H$ is a very interesting production mode at the LHC:
  - discover/confirm the Higgs
  - measurement of Top Yukawa coupling
  - SM? New Physics?

- It is crucial to know the impact of QCD corrections.

- The NLO inclusive total cross section to $p\bar{p} \to t\bar{t}H$ at the Tevatron and $pp \to t\bar{t}H$ at the LHC has been calculated independently by two groups:
  \[ \sigma_{\text{NLO}}(p\bar{p} \to t\bar{t}H) : \text{W.Beenakker et al., PRL 87 (2001)} \]

\[ \rightarrow \text{The two calculations are in good agreement.} \]

- The NLO inclusive total cross section to $pp \to t\bar{t}H$ has been calculated independently by two groups:
  \[ \sigma_{\text{NLO}}(pp \to t\bar{t}H) : \text{W.Beenakker et al., PRL 87 (2001)} \]

\[ \rightarrow \text{The two calculations are in good agreement.} \]
• At NLO the factorization/renormalization scale dependence is strongly reduced.

• The remaining theoretical uncertainty from $\mu$ variation is estimated to be about $10 - 15\%$ (Tevatron) and $15 - 20\%$ (LHC).

• At the Tevatron the $\mathcal{O}(\alpha_s)$ corrections slightly reduce $\sigma_{\text{LO}}$ for $m_t < \mu < 2m_t$ ($K = 0.7 - 0.95$).

• At the LHC the $\mathcal{O}(\alpha_s)$ corrections slightly enhance $\sigma_{\text{LO}}$ for $m_t + M_H / 2 < \mu < 4m_t + 2M_H$ ($K = 1.2 - 1.4$).

• Possible improvement: Resummation of large logarithmic corrections at the $t\bar{t}h$ threshold.
\( \frac{d\sigma_{t\bar{t}H}}{d\sqrt{\hat{s}}} \) and \( \frac{d\sigma_{t\bar{t}}}{d\sqrt{\hat{s}}} \) at the Tevatron when only

including \( \mathcal{O}(\alpha_s) \) corrections:

\[ \frac{d\sigma_{t\bar{t}h}}{d\sqrt{\hat{s}}} \text{ [pb/GeV]}, \frac{d\sigma_{t\bar{t}}}{d\sqrt{\hat{s}}} \text{ [nb/GeV]} \]
3. Associated $b\bar{b}$ Higgs production at hadron colliders

$gg, q\bar{q} \rightarrow b\bar{b}h$ at $pp$ and $p\bar{p}$ colliders is dominated by the $gg$ initiated process.

The calculation of the $\mathcal{O}(\alpha_s)$ corrections to $gg, q\bar{q} \rightarrow b\bar{b}h$ is technically similar to $t\bar{t}h$ production. We “simply” replace $m_t$ by $m_b$.

However, there are differences:

$\rightarrow$ We consider both the $OS$ scheme and the $\overline{MS}$ scheme when renormalizing the $b$ quark mass in the $b$ Yukawa coupling:

- $OS$: $g_{bbh} = m_b/v$ with $m_b$ being the pole mass
- $\overline{MS}$: $g_{bbh} = \overline{m}_b(\mu)/v$ with $\overline{m}_b(\mu)$ being the running mass $\Rightarrow$ Possible improvement of perturpative calculation by resumming large logarithmic contributions to the $b\bar{b}h$ vertex.

$\rightarrow$ The contribution from the closed top quark loops is included, e.g.:
The $b\bar{b}h$ processes are classified according to how many $b$ quarks are identified: 2 $b$ quarks tagged, 1 $b$ quark tagged and the fully inclusive case.

In the $2(1)$-$b$-tag case we require two(one) high $p_T$ $b$ quark jets in the final state:

$$p_T^{b, \bar{b}} > 20 \text{ GeV} \quad \text{and} \quad |\eta_{b, \bar{b}}| < 2(2.5) \quad \text{Tevatron (LHC)}$$

Moreover, we consider the radiated gluon and the $b/\bar{b}$ quarks as distinct particles only if

$$\Delta R = \sqrt{(\Phi_b - \Phi_g)^2 + (\eta_b - \eta_g)^2} > 0.4$$

Otherwise their 4-momentum vectors are combined into an effective $b/\bar{b}$ momentum vector.
Exclusive $b\bar{b}$ Higgs production at hadron colliders

→ Requiring two high $p_T$ $b$ quark jets in the final state reduces the signal, but also greatly reduces the background.

→ Unambiguously proportional to the $b$ quark Yukawa coupling.

Status:
Two independent calculations based on $gg, q\bar{q} \rightarrow b\bar{b}h$ at NLO QCD by S.Dittmaier, M.Krämer, M.Spira (hep-ph/0309204) and S.Dawson, C.Jackson, L.Reina, D.W. (PRD 69 (2004)). They are in good agreement.
dependence in the MSSM

\[ M_{(h^0, H^0)}, \tan \beta \text{ dependence in the MSSM} \]

\[ pp \rightarrow b\bar{b}H^0 + X \text{ at the LHC} \]

\[ p\bar{p} \rightarrow b\bar{b}h^0 + X \text{ at the Tevatron} \]

\[
\begin{align*}
\sqrt{s} &= 14 \text{ TeV} \\
p_T^b &> 20 \text{ GeV} \\
|\eta| &< 2.5 \\
\mu & = m_b + M_h/2 \\
\end{align*}
\]

\[
\begin{align*}
\sqrt{s} &= 2 \text{ TeV} \\
p_T^b &> 20 \text{ GeV} \\
|\eta| &< 2 \\
\end{align*}
\]

\[ \sigma_{\text{NLO}} (\text{MSSM}) \sim \sigma_{\text{NLO}} (\text{SM}) \left( \frac{g_{\text{bbh}}^{\text{MSSM}}}{g_{\text{bbh}}} \right)^2 \]

To a good approximation the MSSM result can be obtained from the SM result as follows:

Main Result

Drastically reduced scale dependence of the NLO QCD cross sections:

\[ p\bar{p} \rightarrow b\bar{b}h + X \text{ at the Tevatron} \]

\[ \sqrt{s}=2 \text{ TeV} \]
\[ M_h=120 \text{ GeV} \]
\[ \mu_0=m_b+M_h/2 \]
\[ p_T^b>20 \text{ GeV} \]
\[ |\eta|<2 \]

\[ \sigma_{\text{LO,NLO}} \]
\[ \sigma_{\text{NLO,OS}} \]
\[ \sigma_{\text{NLO,MS}} \]
\[ \sigma_{\text{LO,OS}} \]
\[ \sigma_{\text{LO,MS}} \]

\[ \text{from } S.\text{Dawson, C.Jackson, L.Reina, D.W., PRD 69 (2004)} \]


The b quark mass used in \( g_{bbh} \) is renormalized either in the on-shell (OS) or \( \overline{MS} \) scheme
(\( \overline{MS} \): LO with 1-loop and NLO with 2-loop running mass).
Effect of NLO QCD corrections on the Higgs $p_T$ distribution:

**Inclusive and semi-inclusive $b\bar{b}$ Higgs production at hadron colliders**


**Status:** There exist two approaches, dubbed *variable (or five) flavor number scheme* (VFS) and *fixed (or four) flavor number scheme* (FFS):

→ **FFS approach**

Fixed order, explicit matrix element calculation based on the parton level processes $gg, q\bar{q} \rightarrow b\bar{b}h$.

**Inclusive (no $b$ tagged) and semi-inclusive (1 $b$ tagged): known at NLO QCD**

Two independent calculations by

S.Dittmaier, M.Krämer, M.Spira and S.Dawson, C.Jackson, L.Reina, D.W.

→ These two calculations are in good agreement.

→ **VFS approach**

Use of $b$ quark PDFs to sum to all orders large logs, $\alpha_s \ln(m_b^2/\mu_F^2) (\mu_F \approx M_h)$, which arise due to initial-state $g \rightarrow b\bar{b}$ splitting.
→ VFS approach

Inclusive (no $b$ tagged): known at NNLO QCD

$b$ quark fusion, $b\bar{b} \rightarrow h$, is the leading order subprocess of $\mathcal{O}(\alpha_s^2 \ln^2(M_h/m_b))$ and $b(\bar{b})g \rightarrow b(\bar{b})h$ and $gg, q\bar{q} \rightarrow b\bar{b}h$ are identified as NLO contributions to $b\bar{b} \rightarrow h$ of $\mathcal{O}(1/\ln(M_h/m_b))$ and $\mathcal{O}(1/\ln^2(M_h/m_b))$, respectively.

D.Dicus, F.Maltoni, T.Stelzer, Z.Sullivan, S.Willenbrock

\begin{center}
\includegraphics[width=0.8\textwidth]{diagram.png}
\end{center}

Inclusive $pp, p\bar{p} \rightarrow (b\bar{b})H + X$ production has been calculated at NNLO QCD by R.Harlander, W.Kilgore.

Semi-inclusive (1 $b$-tagged): known at NLO QCD

$b(\bar{b})g \rightarrow b(\bar{b})h$ is the leading order subprocess of $\mathcal{O}(\alpha_s^2 \ln(M_h/m_b))$ and $gg, q\bar{q} \rightarrow b\bar{b}h$ are identified as NLO contributions of $\mathcal{O}(1/\ln(M_h/m_b))$.

J.Campbell, R.K.Ellis, F.Maltoni, S.Willenbrock
Main Result

Drastically reduced scale dependence of the NLO QCD cross sections – 1 b tagged:

![Graphs showing the scale dependence of LO and NLO cross sections for √s=1.96 TeV and √s=14 TeV.](image)

\[ \sqrt{s}=1.96 \text{ TeV} \]
\[ M_h=120 \text{ GeV} \]
\[ \mu_0=m_b+M_h/2 \]
\[ \text{CTEQ6} \]
\[ 1\text{b–tag} \]

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preliminary

from S.Dawson, C.Jackson, L.Reina, D.W., in preparation

Main Result

Drastically reduced scale dependence of the NLO QCD cross sections – no b tagged:

from S.Dawson, C.Jackson, L.Reina, D.W., in preparation

$M_h$ dependence – 1 b tagged

Comparison with $b$ quark PDF approach by J.Campbell, R.K.Ellis, F.Maltoni, and S.Willenbrock:

$gg, q\bar{q} \rightarrow b\bar{b}h$: from S.Dawson, C.Jackson, L.Reina, D.W., in preparation, see also S.Dittmaier et al., hep-ph/0309204

$gb(\bar{b}) \rightarrow b(\bar{b})h$: from J.Campbell et al. in LesHouches 2003 procs. (hep-ph/0405302)

and closed top quark loop added to MCFM (J.Campbell et al., PRD67 095002 (2003))
$M_h$ dependence – $0\ b$ tagged (VFS)


$$\mu_F = (0.1, 0.7)M_h, \mu_R = M_h$$
Effect of NLO QCD corrections on the Higgs $p_T$ distribution:

LHC

from S.Dawson, C.Jackson, L.Reina, D.W., in prep.
Effect of NLO QCD corrections on the Higgs $p_T$ distribution:

from S.Dawson, C.Jackson, L.Reina, D.W., in prep.
Summary for $b\bar{b}h$

- $b\bar{b}h$ is an important Higgs production mode in models with an enhanced $b$ quark Yukawa coupling, e.g. for large values of $\tan \beta$ in the 2HDM, MSSM.
- It is crucial to know the impact of QCD corrections.
- There has been considerable improvement in obtaining stable QCD predictions for inclusive, semi-inclusive and exclusive Higgs production in association with $b$ quarks (for a review see, e.g., J.Campbell et al., LesHouches 2003 proceedings, hep-ph/0405302):
  - In all three cases, at NLO (NNLO) QCD the factorization/renormalization scale dependence is strongly reduced.
- $p\bar{p}, pp \to b\bar{b}h$ production has been calculated at NLO QCD based on the $gg, q\bar{q} \to b\bar{b}h$ parton level processes independently by two groups:
  - The two calculations are in good agreement.
  - Results have been obtained for the inclusive, semi-inclusive and exclusive case.
In the exclusive case (2 b-tagged), the remaining theoretical uncertainty is estimated to be about $15 - 20\%$ (Tevatron,LHC) due to residual scale dependence and about $15 - 20\%$ (Tevatron,LHC) due to $b$ quark Yukawa coupling renormalization scheme dependence.

- Semi-inclusive $b(\bar{b})h$ production based on $b(\bar{b})g \rightarrow b(\bar{b})h$ has been calculated at NLO QCD using the $b$ quark PDF approach (VFS).

- The two NLO calculations, based on $gg, q\bar{q} \rightarrow b\bar{b}h$ (FFS) and $gb(\bar{b}) \rightarrow b(\bar{b})h$ (VFS) subprocesses, agree within their respective theoretical uncertainties.

- Inclusive $(b\bar{b})h$ production based on $b$ quark fusion, $b\bar{b} \rightarrow h$, is known at NNLO QCD (VFS).

- The predictions based on $gg, q\bar{q} \rightarrow b\bar{b}h$ (FFS) and $b\bar{b} \rightarrow h$ (VFS) subprocesses agree reasonably well within their respective theoretical uncertainties.

- Possible improvement (FFS): Identification and resummation of large logarithms, $\ln(M_h/m_b)$, arising when integrating over the $b$ quark $p_T$. 

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Fermilab Theory Seminar

07/22/04
Conclusion

QCD predictions for total cross sections to Higgs production processes at hadron colliders are under good theoretical control:

\[
\sigma[\text{pb}] \quad \text{Tevatron, } M_h/2 < \mu < 2M_h
\]

from S.Dawson et al., hep-ph/0210109

\( t\bar{t}h: \mu \) varied between \( \mu_0 = m_t + M_h/2 \) and \( 2\mu_0 \).

from S.Dawson et al., in prep. (prelim.)