Higgs Boson Production with Bottom Quarks at Hadron Colliders

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SM Higgs Production at Hadron Colliders

(From M. Carena, H. Haber, Prog.Part.Nucl.Phys.50(2003))

- In SM, Higgs production dominated by $gg \rightarrow h$
- $b\bar{b}h$ suppressed due to smallness of $g_{hbb} \sim \frac{m_b}{v}$
MSSM Higgs Production at Hadron Colliders

(from M. Carena, H. Haber, Prog.Part.Nucl.Phys.50(2003))

- Yukawa coupling enhanced: \( g^{MSSM}_{bb(h^0,H^0)} = \frac{(-\sin \alpha, \cos \alpha)}{\cos \beta} g_{bbh} \)

- \( \sigma_{(h^0,H^0)b\bar{b}} \) comparable or larger than \( \sigma_{gg \rightarrow (h^0,H^0)} \)
Four Flavor Number Scheme (4FNS)

- Tagging $b$ jets:
  - inclusive $\equiv$ no cuts on $p_T$ of $b$'s
  - semi-inclusive $\equiv$ one high-$p_T$ $b$
  - exclusive $\equiv$ two high-$p_T$ $b$'s

- (Semi-)Inclusive c.s. develops potentially large log’s ($\Lambda_b \equiv \log\left(\frac{Q^2}{m_b^2}\right)$) from collinear splitting ($g \to b\bar{b}$)

- Perturbative expansion: $\alpha_s \to \alpha_s \Lambda_b$
Exclusive $b\bar{b}h$ Production

- Two independent calculations of NLO QCD corrections:

- Setup:
  - Require two high-$p_T$ $b$ jets in final state: $p_T^{b,\bar{b}} > 20$ GeV and $|\eta_{b,\bar{b}}| < 2(2.5)$ Tevatron (LHC)
  - Radiated $g$ and $b/\bar{b}$ distinct only if $\Delta R > 0.4$

- Cuts reduce signal and background

- Factorization/renormalization scale dependence reduced

- Given large sensitivity of $m_b(\mu_r)$ on $\mu_r$, also investigated renormalization scheme dependence for $m_b$
  - $OS$ vs. $\overline{MS}$: at $\mathcal{O}(\alpha_s^3)$ both are perturbatively consistent
  - Difference being at higher orders $\rightarrow$ theoretical uncertainty $\approx 15 - 20\%$
Results for Exclusive $\bar{b}b\bar{b}h$ Production

(from S. Dawson, C.J., L. Reina and D. Wackeroth, PRD 69, 074027 (2004))
$M_H$, $\tan \beta$ Dependence for Exclusive $b\bar{b}(h^0, H^0)$

(from S. Dawson, C.J., L. Reina, D. Wackeroth, PRD 69,074027 (2004))

- Large $\tan \beta \rightarrow$ top loop suppressed
- Good approximation: $\sigma_{NLO}(MSSM) \sim \sigma_{NLO}(SM)(\frac{g_{bbh}^{MSSM}}{g_{bbh}^{SM}})^2$
Five Flavor Number Scheme (5FNS)

- Physical process $gg \rightarrow b\bar{b}h$ contains large logs from (collinear) splitting $g \rightarrow b\bar{b}$

- Introduce (theoretically defined) $b$-quark PDF:

\[
\tilde{b}(x, \mu) = \frac{\alpha_s(\mu)}{2\pi} \log\left(\frac{\mu^2}{m_b^2}\right) \int_x^1 \frac{dy}{y} P_{qg}(\frac{x}{y}) g(y, \mu)
\]

- Leading Processes in 5FNS:
  - **Inclusive** $\equiv b\bar{b} \rightarrow h$ (Known at NNLO (see Harlander & Kilgore PRD 68 (2003) 013001))
  - **Semi-inclusive** $\equiv gb \rightarrow bh$ (Known at NLO (see Campbell et.al PRD 67 (2003) 095002))

- Important to study validity/compatibility of 4FNS/5FNS
Results for Inclusive \((\bar{b}b)h\) Production

(from J. Campbell et. al. (Higgs Working Group), Les Houches workshop on Physics at TeV Colliders (2004), hep-ph/0405302)
Results for Semi-inclusive $b(\bar{b})h$ Production

\[ \sigma(pp \to b\bar{b}h + X) \text{ [fb]} \]
\[ \sqrt{s} = 1.96 \text{ TeV} \]
\[ M_h = 120 \text{ GeV} \]
\[ \mu = (2m_b + M_h)/4 \]
\[ p_T^{b\bar{b}} > 20 \text{ GeV} \]
\[ |\eta_b\bar{b}| < 2 \]
\[ gb/b \to b\bar{b}h \]
\[ gg \to bb + h \]

$\sigma_{LO,NLO}$ vs $\mu/\mu_0$ for $\sqrt{s}=1.96$ TeV and $M_h=120$ GeV.

$\sigma_{LO,NLO}$ vs $M_h$ for $\sqrt{s}=14$ TeV and $M_h=120$ GeV.

$\sigma_{LO,NLO}$ vs $\mu/\mu_0$ for $\sqrt{s}=14$ TeV and $M_h=120$ GeV.
Not the End of the Story

- Diagrams containing loops of quarks neglected in 5FNS

\[ 
\begin{align*}
\text{b} & \quad \text{g} \quad \text{h} \\
\text{t} & \quad \text{h} \\
\text{b} & \quad \text{b}
\end{align*}
\]

- \( bg \rightarrow bh \) @ NLO performed in the \( m_b = 0 \) approximation (except in \( g_{hbb} \)):
  - Top quark loop neglected since \( g_{(h^0,H^0)tt} \approx \frac{1}{\tan \beta} \)
  - Bottom quark loop neglected since amplitude is \( \propto m_b \)
  - In SM, this diagram (w/ top quarks) makes a contribution \( \sim \mathcal{O}(g_{Hbb}^2) \rightarrow \) could be numerically important!

- To compare 4FNS and 5FNS for semi-inclusive process, we utilized MCFM (Campbell and Ellis, webpage:mcfm.fnal.gov) altered to contain the top loop contribution.

- Including top loop lowers \( \sigma_{gb \rightarrow bh} \) by 15%(10%) at the Tevatron (LHC)
Results for Semi-inclusive $b(\bar{b})h$ Production ...again

For $\tan \beta = 40$, top loop contribution $\leq 0.08\%$ in $gb \rightarrow bh$
Summary

- $b\bar{b}h$ can play important role in Higgs production at Hadron Colliders for models w/ enhanced $b$ quark Yukawa couplings (e.g. 2HDM, MSSM)

- QCD corrections can have large effects on distributions and drastically reduce theoretical uncertainties

- **Exclusive Production**: agreement between two independent NLO QCD calculations

- **Inclusive Production**: “good” agreement between 4FNS and 5FNS calculations (top loop diagrams?)

- **Semi-inclusive Production**:
  - Academically: SM results now agree (spectacularly!) between 4FNS and 5FNS after the inclusion of the top loop diagrams in $gb \to bh$
  - Numerically: MSSM results agree between 4FNS and 5FNS
Further Reading

- **Exclusive Production:**

- **Inclusive and Semi-inclusive Production:**
  - Harlander and Kilgore (PRD 68 013001(2003))
  - J. Campbell et. al. (PRD 67 095002 (2003))

- **Comparison between 4FNS/5FNS:**
  - LH HWG (hep-ph/0405302)
$p_T$ Distributions for Semi-inclusive Production

“Divergences” in $p_T$ Distributions

- Similar effects seen in Drell-Yan $Q_\perp$ distributions (for review, see S. Catani and B.R. Webber, hep-ph/9710333)

- At LO, Higgs recoils against $b$ jet:
  - $p_T$ cut on $b$ jet $\implies$ cut on $p_T^h$
  - $(\frac{d\sigma}{dp_T^h})_{LO} \rightarrow$ “non-smooth” function

- In the region of the “cut” on $p_T^h$, the NLO c.s. is the convolution of the LO c.s. with a “soft gluon probability”
  - ”Soft gluon probability” $\rightarrow$ “plus” distribution
    
    \[
    \text{“non-smooth” } f(z) = \int_0^1 dz f(z)[g(z)]_+ = \text{“logarithmic divergences”}
    \]

- Improvement through resummation techniques (see, e.g. N. Kidonakis, hep-ph/9902484)