Higgs Bosons and b Quarks

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SM Production Mechanisms at LHC

Production with b’s very small in SM

- Information about $b\bar{b}H$ coupling must come from decays
- Progress in extracting $H\rightarrow b\bar{b}$ from boosted Higgs techniques [Plehn]
Higgs Couplings Very Different in MSSM

H, A couplings to d, s, b enhanced at large $\tan \beta$

$h$ couplings to d, s, b enhanced at large $\tan \beta$ for small $M_A$
Relative Importance of Production Modes

\[ \sigma_{gg} = \frac{1}{M_h^2} \left( c_1 \cot^2 \beta + c_2 \frac{m_b^2}{M_h^2} + c_3 \frac{m_b^4}{M_h^4} \tan^2 \beta \right) \]

\[ \sigma_{bb} = \frac{m_b^2}{M_h^4} c_4 \tan^2 \beta \]

⇒ At some \( \tan \beta \), the rates for \( \bar{b}b \rightarrow A,H,h \) will be larger than those for \( gg \rightarrow A,H,h \)
$pp, p\bar{p} \rightarrow b\bar{b}H$

Rates large even at relatively small $\tan \beta$

\[\alpha_{\text{eff}} \text{ from } \text{FeynHiggs with } M_{\text{SUSY}}=M_g=\mu=M_2=1 \text{ TeV, } A_b=A_t=25 \text{ GeV}\]
QCD Corrections Important

- NLO corrections improve scale dependence
- NLO QCD corrections large (can’t neglect them!)
- In 4 flavor number scheme:
  * Corrections don’t exist in public code

Dawson, Jackson, Reina, Wackeroth, hep-ph/0408077,0508293
Dittmaier, Kramer, Spira, hep-ph/0309204
Residual Scheme Dependence at NLO

- Cross section proportional to b Yukawa, \( \lambda_b^2 \approx \left( \frac{m_b^2}{v^2} \right) \)
- \( \overline{\text{MS}} \) vs on-shell definitions of b quark mass
- \( \overline{\text{MS}} \) mass depends on physical scale: \( \bar{m}_b(\mu) = m_b \left[ 1 - \frac{\alpha_s}{3\pi} \left( 4 + 3 \ln \left\{ \frac{\mu^2}{m_b^2} \right\} \right) \right] \)
- Difference between schemes is \( \text{O}(\alpha_s^4) \)

\[ pp \rightarrow b\bar{b}h \]

\[ \text{Renormalization scheme dependence} \]

\[ \text{Scale dependence} \]

- Large scheme dependence at NLO
- Effect \( \approx 10-20\% \)
Theoretical Issues in $b\bar{b}h$ production

Reduced \[ \downarrow \]
Background \[ \uparrow \]

- **Inclusive mode**: No tagged $b$'s
- **Semi-inclusive mode**: At least one tagged $b$
- **Exclusive mode**: Two tagged $b$'s

- Treating $b$ quarks inclusively leads to large collinear logarithms from integration over phase space

\[ \mu_F \approx M_h \]

- Expansion parameter becomes $\alpha_s \log(m_b/M_h)$
Two Schemes for PDFs

• **4 flavor number scheme (Fixed Flavor Number Scheme)**
  – No b quarks in initial state
  – Lowest order process involving Higgs and b’s is $gg \rightarrow bbh$
  – No kinematic approximations

• **5 flavor number scheme (Variable Flavor Number Scheme)**
  – Define b quark PDFs (absorbs large logarithms)
    \[
    b(x, \mu) = \frac{\alpha_s}{2\pi} \ln\left( \frac{\mu^2}{m_b^2} \right) \int_x^1 \frac{dz}{z} P_{bg} \left( \frac{x}{z} \right) g(z, \mu)
    \]
  – Higgs produced with no $p_T$ at lowest order ($b\bar{b} \rightarrow h$)
  – Higgs $p_T$ generated at higher orders in expansion
  – Both CTEQ and MSTW use this scheme for PDFs
Re-ordering of Perturbation Theory

• 0 b tag process in 5FNS:
  – LO: $b\bar{b} \rightarrow h$ $O(\alpha_s^2 \Lambda_b^2)$
  – NLO: Virtual + real corrections $O(\alpha_s^3 \Lambda_b^2)$
  – NLO: $bg \rightarrow bh$ $O(\alpha_s^2 \Lambda_b)$, correction of $O(1/\Lambda_b)$
  – NNLO: $gg \rightarrow b\bar{b}h$ $O(\alpha_s^2)$, correction of $O(1/\Lambda_b^2)$

• 1 b tag process in 5FNS:
  – LO process is $bg \rightarrow bh$: Tree level, $O(\alpha_s^2 \Lambda_b)$
  – NLO includes new subprocess: $gg \rightarrow b\bar{b}h$, $O(1/\Lambda_b)$ correction

$\Lambda_b = \log(M_h^2/m_b^2)$

4FNS and 5FNS must agree at high enough order in perturbation theory
Inclusive Cross Section for $\bar{b}b \to h$: 0 $b$ tags

$\bar{b}b \to h$ vs $gg \to \bar{b}bh$

**4FNS:** NLO QCD

**5FNS:** NNLO QCD

Agreement best at low $M_h$

**S-ACOT Scheme:** $\sigma_{tot} \approx \sigma_{bb} + \sigma_{sub} + \sigma_{gg}$

$\sigma_{sub}$ takes care of double counting from $g \to \bar{b}b$

LHC Higgs cross section group, Freiburg, 3/10

Harlander, Kilgore, hep-ph/0304035; public code bbh@NNLO
Issues with Factorization Scale Dependence?

$5FNS, \bar{b}b \to h @NNLO, MSTW2008, \sqrt{s}=7$ TeV

$0.2M_H < \mu_R < 5M_H$

$0.1M_H < \mu_F < 0.7M_H$

LHC Higgs cross section group, Freiburg, 3/10
PDF uncertainty for $b\bar{b}\rightarrow h$

5FNS, $b\bar{b}\rightarrow h$ @NNLO,
MSTW2008, $\sqrt{s}=7$ TeV

Large PDF uncertainty for heavy Higgs!

LHC Higgs cross section group, Freiburg, 3/10
SUSY QCD / Electroweak Corrections

- Compute in effective Lagrangian approach

\[ L_{\text{eff}} = \frac{\bar{m}_b(\mu)}{v_{\text{SM}}} \left( -\frac{\sin \alpha}{\cos \beta} \right) \left( 1 + \delta_{\text{SQCD}} + \delta_{\text{EW}} \right) \bar{b} h^0 \]

- SUSY QCD:

\[ \delta_{\text{SQCD}} = \left( \frac{1}{1 + \Delta m_b} \right) \left( 1 - \frac{\Delta m_b}{\tan \beta \tan \alpha} \right) \]

- Similarly for weak effects: \( \delta_{\text{EW}} \sim 2-4\% \)

Effective Lagrangian approach works to 1-3% for \( bb \rightarrow h \) for SQCD and EW effects

Dittmaier et al, hep-ph/0611353
Carena, Garcia, Nierste, Wagner, hep-ph/9912516
Bottom Line: Inclusive 0 b Tag

- Calculate SM in 5FNS to NNLO (using bbh@NNLO)
  - Find MSSM couplings from HDECAY or FeynHiggs
- $\mu_R$ uncertainty $\sim 5\%$
- $\mu_F$ uncertainty $\sim 5\%$ for $M_H > 200$ GeV, up to 20% for lighter $M_H$
- Scheme dependence $\sim 10-20\%$
- PDF uncertainty $\sim 10-20\%$
- SQCD and EW effects accurately included using effective Lagrangian approach ($\Delta m_b$)
  - These may be large
Easier experimentally: $bH$ production

- **4 flavor number scheme**
  - NLO QCD

- **5 flavor number scheme**
  - NLO QCD [MCFM with top triangle removed]
  - SUSY QCD corrections
  - EW corrections

Consistent results for total cross sections
Compare Distributions: Single $b$ Tag

• 4FNS vs 5FNS: Important differences

\[
\frac{d\sigma}{d\eta_h} \text{ (fb/GeV)} \quad \text{Tevatron} \quad \frac{d\sigma}{d\eta_h} \text{ (pb/GeV)} \quad \text{LHC} \quad \sqrt{s}=14 \text{ TeV}
\]

MSSM with $M_h=120$ GeV, $\tan \beta=40$
Compare distributions: Single b tag

MSSM with $M_h=120$ GeV, $\tan \beta=40$
Calculate SUSY QCD Corrections to bg→bh

- **Approach 1: Improved Born Approximation** ($\Delta m_b$)

  \[ g_{hbb} \equiv m_b \left( \frac{1}{1 + \Delta m_b} \right) - \frac{\sin \alpha}{\cos \beta} \left( 1 - \frac{\Delta m_b}{\tan \beta \tan \alpha} \right) \]

  \[ \sigma_{IBA} = \left( \frac{g_{hbb}^S M}{g_{hbb}^b} \right)^2 \sigma_{LO} \]

- **Approach 2: O($\alpha_s^2$) NLO calculation**
  - Use $g_{hbb}$ as above, so subtract off double counting
  - Include all contributions from squark/gluino loops

  Many contributions not included in IBA
Non-Decoupling of SQCD for Light SUSY (pp → bH)

\[ \tilde{m}_g = \tilde{m}_b = 250 \text{ GeV} \]

Improved Born Approximation fails for light SUSY particles

\[ \tilde{m}_g = \tilde{m}_b = 1 \text{ TeV} \]

Dawson & Jackson, arXiv:0709.4519
Do Electroweak Corrections Matter?

- Lowest order rate for $bg \rightarrow bh$ vanishes for $m_b = 0$
- At 1-loop, there are diagrams which do NOT vanish in $m_b = 0$ limit
- Full EW calculation

Plus many more diagrams.....

Mrenna, Yuan, hep-ph/9507235
EW Corrections to $pp \rightarrow bh$

$$\sigma(pp \rightarrow bH) = \sigma_0 \left( 1 + \Delta_{QCD} + \Delta_{SQCD} + \Delta_{EW} \right)$$

Improved Born Approximation captures weak corrections accurately

Dawson & Jaiswal, arXiv:1002.2672
EW corrections in large $M_h$ limit

- Dominant contributions from $b\bar{b}h$ vertex
  - No contributions which grow with $M_h$ from triangle or box diagrams

$$\sigma(bg \rightarrow bh) \approx \sigma_0 \left(1 + \frac{M_h^2}{32\pi v^2} \left[13 - 2\pi\sqrt{3}\right]\right)$$

- Need $\log(M_h)$ pieces to reproduce full calculation
- Corrections $O(18\%)$ for $M_h \sim 1$ TeV

LHC Expectations

$M_A$ (GeV)

QCD and theory uncertainties will change this!
Conclusions

• Compatible answers in 4FNS and 5FNS for total cross sections
  – Distributions in single b tag case slightly different

• EW corrections important at large $M_h$
  – EW corrections for both 0 and 1 b tag can be included with effective Lagrangian

• SUSY QCD corrections can be important for light SUSY
  – For heavy SUSY can include SQCD in effective Lagrangian for single b tag
  – Effective Lagrangian works for all SUSY masses for 0 b tag

• Uncertainties from scheme dependence, PDFs, scale uncertainty significant