Improved transverse momentum distribution for a Higgs boson produced with a bottom quark

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Outline

- Introduction
  - Quick review of SM and MSSM
  - Production channels and problems
  - The process \[ bg \rightarrow b\Phi \Phi = \{h^0, H^0\} \]

- Limits on \( \tan(\beta) \) from Higgs physics

- Fixed-order and Resummation
  - Small transverse momentum \( (p_T) \)
  - Formalism for \( 2 \rightarrow 2 \) processes
  - Results of our study

- Conclusions
Introduction

- Bottom quarks produced in association with a Higgs boson(s) is of great experimental and theoretical interest
- MSSM can have enhanced bottom Yukawa couplings in Higgs sector
- Higher order differential cross-sections for bottom processes are needed to make use of current and future data sets
- Resummation is more reliable at small values of transverse momentum
SM and MSSM Higgs

EWSB: $h^{\text{SM}} \rightarrow \{h^0, H^0, H^\pm, A^0\}$ \quad \tan(\beta) = v_2/v_1

$$\lambda_b^{\text{SM}} = \sqrt{2} \frac{m_b}{v}$$

$$\lambda_b^{\text{MSSM}} = \begin{cases} 
-\sqrt{2} \frac{m_b}{v} \frac{\sin \alpha}{\cos \beta}, & \Phi = h^0 \\
\sqrt{2} \frac{m_b}{v} \frac{\cos \alpha}{\cos \beta}, & \Phi = H^0 \\
\sqrt{2} \frac{m_b}{v} \tan \beta, & \Phi = A^0.
\end{cases}$$
How to make a Higgs

- Higgs couples to mass
- Top quark loop is largest contribution in SM
- Several groups have calculated fixed-order cross-sections to NNLO
How to make a Higgs

- In MSSM, this is not always true
- As $\tan(\beta)$ increases, bottom-quark becomes important
- Both top- and bottom-quarks can be important
How to make a Higgs

- We are interested in bottom-quarks
- Introduce bottom-quark PDFs ($5\text{FNS}$) for convenience
- Potentially large signal in MSSM at large values of $\tan(\beta)$
- $5\text{FNS}$ allows a study of lower order diagrams
How to make a Higgs

- Differential cross-sections are experimentally more useful
- Need extra parton in final state
- $2 \rightarrow 2$ kinematics
  - Allows us to introduce cuts
How to make a Higgs

- We also require bottom-quark tagging
- This is our process in 5FNS
- \( bg \rightarrow b\Phi \) is a preferred study, fixed-order calculations have been completed
- An experimental limit had been set with this process
Limits on $\tan(\beta)$


$MSSM$ Higgs bosons $b\bar{b}\phi(\rightarrow b\bar{b})$, $\phi = h, H, A$

Excluded at LEP

$\tan\beta$

$m_A$ (GeV)

No mixing

Max. mixing
Fixed-order calculations are known to be unreliable at small values of the transverse momentum \( p_T \).

Most of the signal is at small \( p_T \).

Resummation of \( bg \to b\Phi \Phi = \{ h^0, H^0 \} \):
- Understand small-\( p_T \) differential cross-section
- Stronger experimental signal
- Push limit on \( \tan(\beta) \) down further
- We also need to say something about the bottom-quark transverse momentum \( p_T^b \) for tagging.
Traditional Resummation

Resumming Higgs processes is well established

- **Total cross-section resummation**
  - S. Catani, D. de Florian, and M. Grazzini [JHEP 0105 025 (2001)]
  - S. Catani, D. de Florian, M. Grazzini, and P. Nason [JHEP 0307 028 (2003)]

- **Differential cross-section resummation**
  - BJF [Phys. Rev. D 70 054008 (2004)]

The problem with these methods is that it is difficult to impose any **cuts**

How does one calculate a resummed Higgs $p_T^\Phi$ spectrum while imposing $p_T^b > 20$ GeV or rapidity cuts?
1PI Resummation

One-Particle-Inclusive (1PI) Resummation formalism by N. Kidonakis


Here we have all the power of the $2 \rightarrow 2$ kinematics (so we can introduce cuts) but we have the advantages of resummation, plus most **coefficients** have been calculated

\[
S^2 \frac{d^2 \sigma}{dT \, dU} = \int_{x_1^{-}}^{1} \frac{dx_1}{x_1} \int_{0}^{\hat{s}_2^+} \frac{d\hat{s}_2}{\hat{s}_2 - \hat{t} + m_b^2} \phi(x_1) \phi(x_2^*(\hat{s}_2)) \hat{s}^2 \frac{d^2 \hat{\sigma}}{d\hat{t} \, d\hat{u}}
\]

\[
x_2^*(\hat{s}_2) = \frac{\hat{s}_2 + m_b^2 - Q^2 - x_1(T - Q^2)}{x_1 S + U - Q^2}
\]
NLL and NNLL

\[
\hat{s}^2 \frac{d^2 \hat{\sigma}_{i,j}^{(k)}}{dt \, du} = \sum_{ij} \left( \frac{\alpha_s}{\pi} \right)^k \left\{ A^{ij}(\hat{s}_2) \delta(\hat{s}_2) + \sum_{l=0}^{2k-1} a_l^{ij}(\hat{s}_2) \left[ \ln^l(\hat{s}_2/M^2) \right] \right\},
\]

\[
d\hat{\sigma}^{(1)} = d\hat{\sigma}^B \frac{\alpha_s}{\pi} \left\{ c_3 D_1(\hat{s}_2) + c_2 D_0(\hat{s}_2) + c_1 \delta(\hat{s}_2) \right\}
\]

\[
d\hat{\sigma}^{(2)} = d\hat{\sigma}^B \frac{\alpha_s^2}{\pi^2} \left\{ \frac{1}{2} c_3^2 D_3(\hat{s}_2) + \left[ \frac{3}{2} c_3 c_2 - \frac{\beta_0}{4} c_3 \right] D_2(\hat{s}_2)
\]

\[
+ \left[ c_3 c_1 + (C_F + C_A)^2 \ln^2 \left( \frac{\mu_F^2}{Q^2} \right) - 2(C_F + C_A) T_2 \ln \left( \frac{\mu_F^2}{Q^2} \right)
\]

\[
+ \frac{\beta_0}{4} c_3 \ln \left( \frac{\mu_R^2}{Q^2} \right) - \zeta_2 c_3^2 \right] D_1(\hat{s}_2) + \left[ - (C_F + C_A) \ln \left( \frac{\mu_F^2}{Q^2} \right) c_1 - \frac{\beta_0}{4} (C_F + C_A) \ln \left( \frac{\mu_R^2}{Q^2} \right) c_1
\]

\[
+ (C_F + C_A) \frac{\beta_0}{8} \ln^2 \left( \frac{\mu_F^2}{Q^2} \right) - \zeta_2 c_2 c_3 + \zeta_3 c_3^2 \right] D_0(\hat{s}_2) \right\}
\]
Coefficients

\[ bg \rightarrow b\Phi \]

\[ c_1 = \left[ C_F \ln \left( \frac{Q^2 - \hat{u}}{Q^2} \right) + C_A \ln \left( \frac{Q^2 - \hat{t}}{Q^2} \right) - \frac{3}{4} C_F - \frac{\beta_0}{4} \right] \ln \left( \frac{\mu_F^2}{Q^2} \right) + \frac{\beta_0}{4} \ln \left( \frac{\mu_R^2}{Q^2} \right) \]

\[ c_2 = 2C_F \ln \left( \frac{m_b^2 - \hat{t}}{m_b \sqrt{\hat{s}}} \right) + C_A \ln \left( \frac{m_b^2 - \hat{u}}{m_b^2 - \hat{t}} \right) \]

\[ -C_F - 2C_F \ln \left( \frac{Q^2 - \hat{u}}{Q^2} \right) - 2C_A \ln \left( \frac{Q^2 - \hat{t}}{Q^2} \right) - (C_F + C_A) \ln \left( \frac{\mu_F^2}{\hat{s}} \right) \]

\[ c_3 = 2(C_A + C_F) \]
Theoretical Checks

First we needed to check the small-$p_T$ behavior of known fixed-order calculations

- Use the same parameters as fixed-order calculations
  - $M_\Phi = 120$ GeV
  - $p_T^b > 20$ GeV, $|\eta^b| < 2 (2.5)$
  - $\tan(\beta) = 40$
  - $\mu = \mu_0/2$, $\mu_0 = M_\Phi/2 + m_b^{pole}$
  - Bottom-quark $\overline{\text{MS}}$ running mass

- Then we can study other aspects
  - $\mu$-dependence
  - Additional differential quantities
  - Total cross-sections, etc
NLL Resummation Results

Tevatron, CTEQ6.12M

\( M_{h^0} = 120 \text{ GeV}, \tan(\beta) = 40 \)

\( \mu = \mu_0 / 2 \)

4FNS, 5FNS: \( p_T^b > 20 \text{ GeV}, |\eta^b| < 2 \)
NLL Resummation Results

LHC, CTEQ6.12M
$M_{H^0} = 120$ GeV, $\tan(\beta) = 40$
$\mu = \mu_0 / 2$
4FNS, 5FNS: $p_T^b > 20$ GeV, $|\eta^b| < 2.5$
Resummation Results at NNLL

Tevatron, SM Couplings

$M_h = 120 \, \text{GeV}$, $\mu = \mu_0 / 2$

$|\eta^b| < 2$
$\mu$ Dependence

Tevatron, SM Couplings
$\mu = \chi \mu_0$, $M_h = 120$ GeV

$\mu_0 = M_h/2 + m_b^{\text{pole}}$
Total cross-sections
Conclusions

- A Higgs boson(s) produced with bottom-quark(s) is an important discovery channel.
- 1PI Resummation gives us a window into the small $p_T$ behavior of the Higgs while leaving some control over bottom-quark tagging.
- High theoretical confidence in small-$p_T$ region allows for better experimental limits in near future.
- Several other quantities can be studied and combined for better precision.