SQCD Corrections to $bg \to bh$

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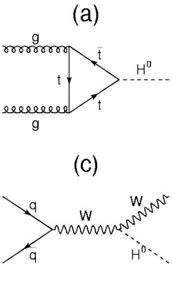
S. Dawson, C. B. Jackson, P. Jaiswal, SUSY QCD Corrections to Higgs-b Production : Is the Δ_b Approximation Accurate?, Phys. Rev. **D83***, 115007 (2011).*

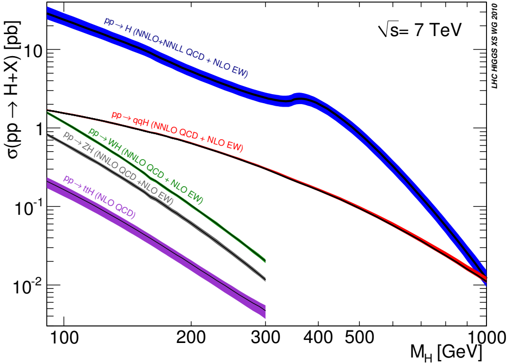
Outline

- Motivation for $bg \to bh$ studies
- 4FNS vs 5FNS
- Large $\tan\beta$ radiative corrections
- SQCD Corrections and Δ_b Approximation
- How good is the Δ_b Approximation?

Motivation

Standard Model Higgs boson Production





- Main production modes in SM : "gluon fusion", W/Z fusion, W/Z associated production and associated production with t
- What about BSM Higgs such as in MSSM?

Motivation

MSSM Higgs Sector

- Two Higgs doublets H_u and $H_d \Rightarrow$
  - 2 CP even (h^0, H^0), 1 CP odd (A^0)
  - 1 charged Higgs (H^+)
  - Goldstone bosons (G^0, G^+)
- VEVs : $\langle H_u \rangle = v_u$ and $\langle H_d \rangle = v_d$, $\tan\beta = v_u / v_d$
- Two independent parameters : m_A and $\tan\beta$ (at tree level)
  - examples : $m^2_{h/H} = \frac{1}{2}\left[m_A^2 + m_Z^2 \mp \sqrt{(m_A^2 + m_Z^2) - 4m_A^2 m_Z^2 \cos^2 2\beta}\right]$
  - α diagonalizes the Higgs mass matrix
    $$\cos 2\alpha = -\cos 2\beta \left(\frac{m_A^2 - m_Z^2}{m_H^2 - m_h^2}\right)$$
- Decoupling limit : $m_A \gg m_Z$
  - $\beta - \alpha \to \frac{\pi}{2}$
  - Significance of Decoupling limit?

Motivation

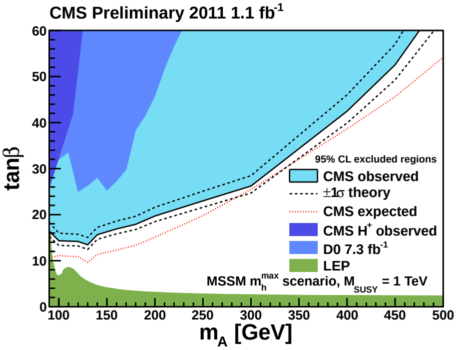
MSSM Higgs Couplings to Fermions

	Couplings w.r.t SM	Decoupling limit
$h^0\bar{b}b$	$-\sin\alpha/\cos\beta$	1
$h^0\bar{t}t$	$\cos\alpha/\sin\beta$	1
$H^0\bar{b}b$	$\cos\alpha/\cos\beta$	$\tan\beta$
$H^0\bar{t}t$	$\sin\alpha/\sin\beta$	$-1/\tan\beta$
$A^0\bar{b}b$	$\gamma_5\tan\beta$	$\gamma_5\tan\beta$
$A^0\bar{t}t$	$\gamma_5\cot\beta$	$\gamma_5\cot\beta$

- Decoupling limit : h^0 couplings in MSSM same as that of SM at tree level (also true for couplings with gauge bosons)
  - Production cross-sections same as that in SM
  - Same channels as SM : gluon fusion, vector boson fusion, associated production
- For $m_A \gtrsim m_h$ and large $\tan\beta$, same conclusions hold (at tree level).

Motivation

- Current status of MSSM parameter space



- Decoupling limit / moderately heavy A and $\tan\beta \gtrsim 7$ good parameter space to study.

Motivation

- Assuming the allowed parameter space (Decoupling limit or moderately heavy A and $\tan\beta \gtrsim 7$), it seems the MSSM lightest CP even Higgs production should be identical to SM.
- Then why (and under what conditions) is production of Higgs in association with bottom quarks important?
- For large $\tan\beta$, the bottom Yukawa gets significantly modified.
  - At tree level, it is SM like
  - Radiative corrections can cause Yukawa to rescale by an order of magnitude.
- For $m_A \lesssim 200$ GeV and $\tan\beta \gtrsim 7$, the dominant Higgs production mode is in association with bottom quark.

4FNS vs 5FNS

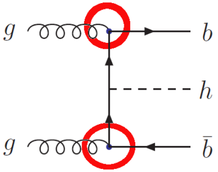
- Higgs production in association with bottom quarks

- $b\bar{b}h$ final state measurements :
  - Exclusive $b\bar{b}h$ production : Both b tagged (high p_T)
  - Semi-inclusive : At least one b tagged
  - Inclusive : No b tagged
- Inclusive modes $\rightarrow$ Larger Cross-section but also large backgrounds.
  $\Rightarrow$ b tagging reduces background
  $\Rightarrow$ Semi-inclusive mode : a good compromise

4FNS vs 5FNS

4FNS (4-parton Flavour Number Scheme)

- Initial state quarks : Four lightest flavours
- *Advantage* :
  - Only way to calculate exclusive $b\bar{b}h$ production (both b tagged)
- *Drawback* :
  - In inclusive $b\bar{b}h$ production, large collinear logs
  - "Fixed order" perturbation theory (No resummation)

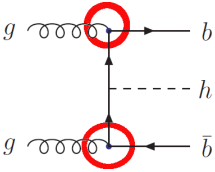


$$\Lambda_b = \ln\left(\frac{\mu^2}{m_b^2}\right)$$

4FNS vs 5FNS

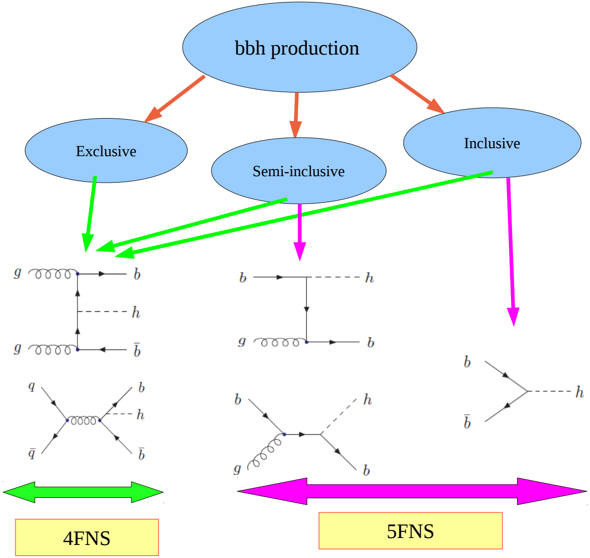
5FNS (5-parton Flavour Number Scheme)

- Addresses the problem of collinear logs
  - Replaces $g \to b\bar{b}$ splitting with initial state b
  - Λ_b logs resummed and absorbed in b-quark PDF
  - Perturbation now in α_s and Λ_b^{-1}
- *Drawback* : Can not be used for exclusive $b\bar{b}h$ production



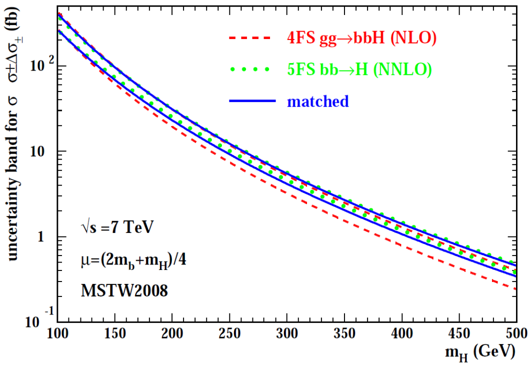
$$\Lambda_b = \ln\left(\frac{\mu^2}{m_b^2}\right)$$

4FNS vs 5FNS


bbh production
Exclusive
Semi-inclusive
Inclusive
4FNS
5FNS

4FNS vs 5FNS

- 4FNS and 5FNS do not match at LO but must match if calculated to all orders.



R. Harlander, M. Kramer, and M. Schumacher,

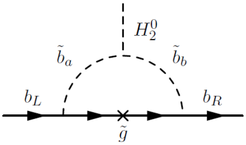
https://twiki.cern.ch/twiki/pub/LHCPhysics/MSSMNeutral/santandermatching-hks.pdf

Large tan β Radiative Corrections

Effective Lagrangian Approach

$$\mathcal{L}_{\rm eff} = -\lambda_b \bar{b}_R \left[H_d + \frac{\Delta\lambda_b}{\lambda_b} H_u^* \right] Q_L$$

- Second term not allowed at tree level in MSSM.
- Effective theory : Integrate out heavy degrees of freedom ($\tilde{g}$, $\tilde{b}$)
- Loop corrections enhanced since $v_u = v_d \tan\beta$

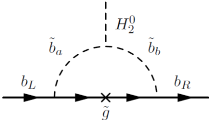


$$m_b \to \lambda_b v_d + \Delta\lambda_b v_u$$
$$= \lambda_b v_d \left(1 + \frac{\Delta\lambda_b}{\lambda_b} \tan\beta \right)$$

Large $\tan\beta$ Radiative Corrections

Effective Yukawa Coupling

- $m_b \to \lambda_b v_d \,(1 + \Delta_b)$
- At one-loop, $\Delta_b \propto \frac{\alpha_s}{\pi} \mu \tan\beta / M_{SUSY}$
- For $\mu \sim M_{SUSY}$, large $\tan\beta$
  $\Rightarrow \Delta_b \sim \mathcal{O}(1)$
- Perturbation in $\alpha_s \tan\beta$, must resum
- Resummation easy since no loop contribution to $\alpha_s^n \tan^n\beta$ for $n \geq 2$!!



Large $\tan\beta$ Radiative Corrections

- Final result : Bare b quark mass in effective Lagrangian approach

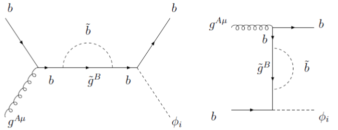
$$m_b = \frac{m_b}{(1+\Delta_b)},$$

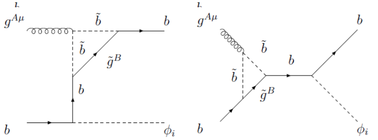
- effective Yukawa coupling :

$$\lambda_b = \frac{m_b}{v_d(1+\Delta_b)}\left(1 - \frac{\Delta_b}{\tan\alpha\tan\beta}\right), \text{ where}$$
$$\Delta_b = \frac{2\alpha_s}{3\pi} M_{\tilde{g}}\mu\tan\beta\,\mathcal{F}(M_{\tilde{b}_1}, M_{\tilde{b}_2}, M_{\tilde{g}})$$

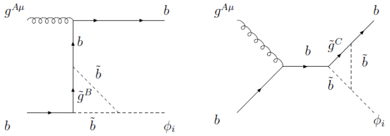
SQCD Corrections

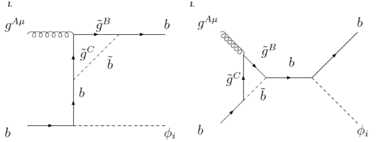
- Complete SQCD one-loop corrections to $bg \to bh$ computed in
  [S. Dawson and C. Jackson, Phys. Rev. D77, 015019 (2008)] ,
  [S. Dawson, C. Jackson and PJ, Phys. Rev. D77, 015019 Phys.Rev. D83 (2011) 115007]
- SUSY QCD $\Rightarrow$ Diagrams involving gluinos and sbottoms





Self-Energy diagrams

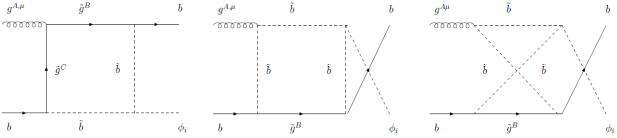




hbb Vertex diagrams

gbb Vertex diagrams

SQCD Corrections



Box diagrams

..... and counterterms

- For cross-section calculations, consider two cases :
  - Maximal mixing case :
    $|\tilde{m}_L^2 - \tilde{m}_R^2| \ll m_b|X_b| \Rightarrow \theta_{\tilde{b}} \sim \frac{\pi}{4}$
  - Minimal mixing case :
    $|\tilde{m}_L^2 - \tilde{m}_R^2| \gg m_b|X_b| \Rightarrow \theta_{\tilde{b}} \sim 0$

- Squark mass matrix :

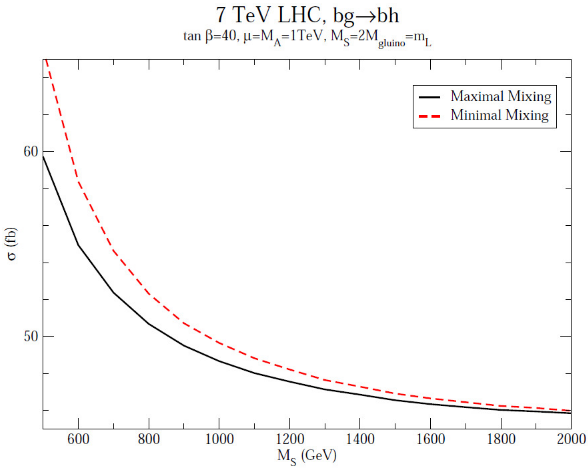
$$M_{\tilde{b}}^2 = \begin{pmatrix} \tilde{m}_L^2 & m_b X_b \\ m_b X_b & \tilde{m}_R^2 \end{pmatrix}$$

$$X_b = A_b - \mu \tan\beta$$

- Mixing angle :

$$\sin 2\theta_{\tilde{b}} = \frac{2m_b\left(A_b - \mu \tan\beta\right)}{M_{\tilde{b}_1}^2 - M_{\tilde{b}_2}^2}$$

SQCD Corrections



- Maximal mixing case : $m_R = m_L = M_S$
- Minimal mixing case : $m_R = \sqrt{2}M_L = \sqrt{2}m_S$

- How much of the SQCD corrections accounted by Δ_b approximation?

SQCD Corrections : Δ_b Approximation

- Δ_b Approximation : Calculate SM cross-section but with rescaled Yukawa coupling

$$\frac{g_{\bar{b}bh}^{MSSM}}{g_{\bar{b}bh}^{SM}} = -\frac{\sin\alpha}{\cos\beta}\left(\frac{1}{1+\Delta_b}\right)\left(1-\frac{\Delta_b}{\tan\beta\tan\alpha}\right)$$

- Includes only resummed large $\tan\beta$ effects.

$M_{SUSY}=1$ TeV, $M_{\tilde{g}}=1$ TeV, $A_b=A_t=2$ TeV, and $\mu=M_2=200$ GeV

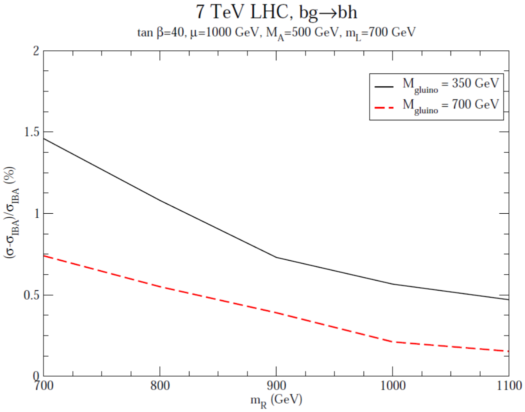
$\tan\beta = 40$				
M_{h^0} [GeV]	100	110	120	130
α [rad]	-1.5063	-1.4716	-1.3798	-0.7150
$g_{b\bar{b}h^0}^{MSSM}/g_{b\bar{b}h}^{SM}$	33.913	33.823	33.387	22.390
$g_{t\bar{t}h^0}^{MSSM}/g_{t\bar{t}h}^{SM}$	0.0645	0.0991	0.1899	0.7553

S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth, Mod.Phys.Lett. A21 (2006) 89-110

SQCD Corrections : Δ_b Approximation

- Δ_b Approximation in the context of $bg \to bh$:

$$\sigma_{MSSM} = \sigma_{SM} \left(\frac{g^{MSSM}_{\bar{b}bh}}{g^{SM}_{\bar{b}bh}} \right)^2 \equiv \sigma_{IBA}$$



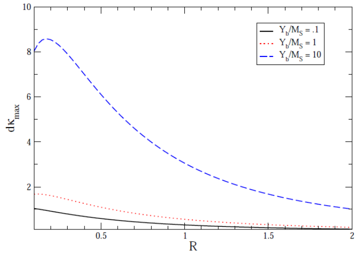
- IBA works very well !!
- Other SQCD corrections < 2 %

Δ_b Approximation : Why it works?

[S. Dawson, C. Jackson and PJ, Phys. Rev. D77, 015019 Phys.Rev. D83 (2011) 115007]

- Analytically compute the SQCD Corrections for two extreme cases : maximal and minimal mixing
- Maximal mixing : $|\tilde{m}_L^2 - \tilde{m}_R^2| \ll m_b |X_b| \Rightarrow \theta_{\tilde{b}} \sim \frac{\pi}{4}$
- Expand the amplitudes in power of $1/M_S$ assuming large $\tan\beta$ so that the terms like $m_b \tan\beta \sim \mathcal{O}(M_{EW})$.

$$|\overline{\mathcal{A}}|^2_{max} = -\frac{2\pi\alpha_s(\mu_R)}{3}(g_{bbh}^{\Delta_b})^2 \left\{ \left(\frac{u^2+M_h^4}{st}\right)\left[1+2\left(\frac{\delta g_{bbh}}{g_{bbh}}\right)^{(2)}_{max}\right] + \frac{\alpha_s(\mu_R)}{2\pi}\frac{M_h^2}{M_S^2}\delta\kappa_{max}\right\} + \mathcal{O}\left(\left[\frac{M_{EW}}{M_S}\right]^4, \alpha_s^3\right).$$



$R = M_{\tilde{g}}/M_S$

- First term : IBA
- Other terms are $\mathcal{O}(M_{EW}^2/M_S^2)$

Conclusion

- Higgs production in association with b quark an important mode for large parameter space in MSSM
- SUSY QCD corrections to $bg \to bh$ can be big for large $\tan\beta$.
- Bottom Yukawa coupling scales by an order of magnitude when large $\tan\beta$ corrections resummed.
- SUSY QCD corrections are dominated by this rescaling : Δ_b approximation works.