Higgs boson production with one bottom quark including higher-order soft-gluon corrections

Resummation at NNNLO-NLL

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arXiv:0705.0035 [hep-ph]

Outline

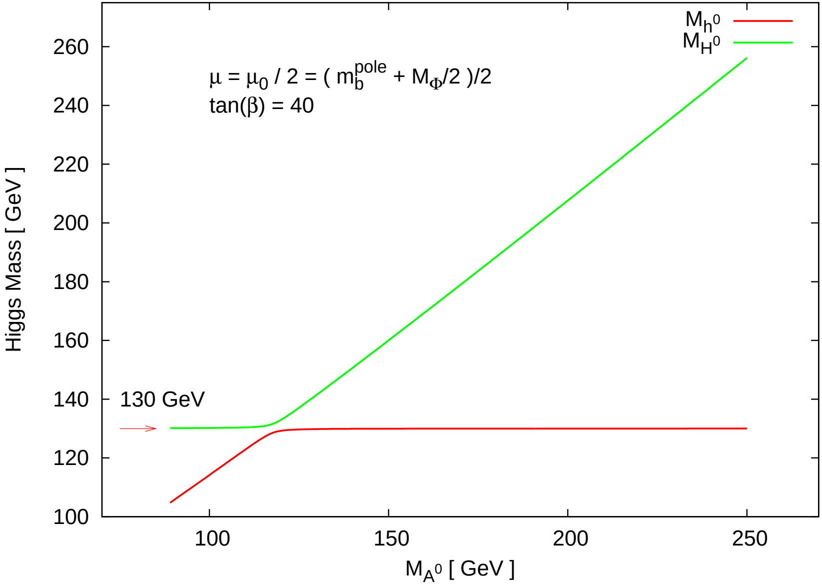
1. Introduction
   - Review of SM and MSSM Higgs
   - How to make a Higgs
   - Limits on tan(β)
2. Resummation Results
   - 1PI Formalism
   - Differential Distributions
   - Scale Dependence
   - Total Cross Sections

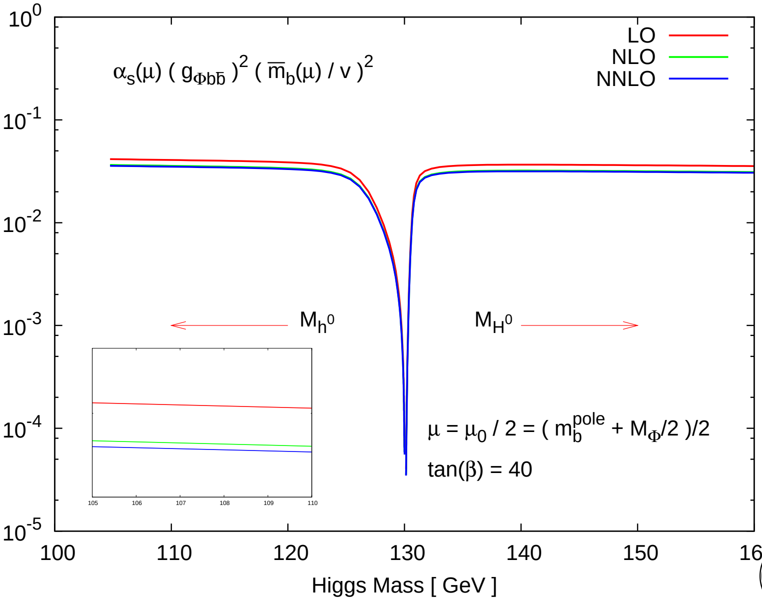
Outline

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

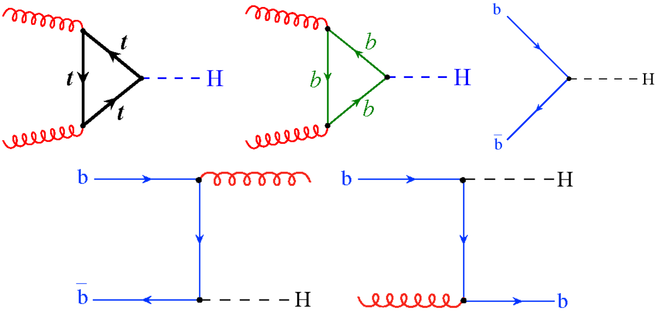
$$\lambda_b^{\text{SM}} = \sqrt{2}\frac{\overline{m}_b}{v}$$

$$\lambda_b^{\text{MSSM}} = \begin{cases} -\sqrt{2}\,\dfrac{\overline{m}_b}{v}\,\dfrac{\sin\alpha}{\cos\beta}\,, & \Phi = h^0 \\ \sqrt{2}\,\dfrac{\overline{m}_b}{v}\,\dfrac{\cos\alpha}{\cos\beta}\,, & \Phi = H^0 \\ \sqrt{2}\,\dfrac{\overline{m}_b}{v}\,\tan\beta\,, & \Phi = A^0. \end{cases}$$


M_{h^0}
M_{H^0}
$\mu = \mu_0 / 2 = (m_b^{pole} + M_\Phi/2)/2$
$\tan(\beta) = 40$
130 GeV
Higgs Mass [GeV]
M_{A^0} [GeV]
260
240
220
200
180
160
140
120
100
100
150
200
250

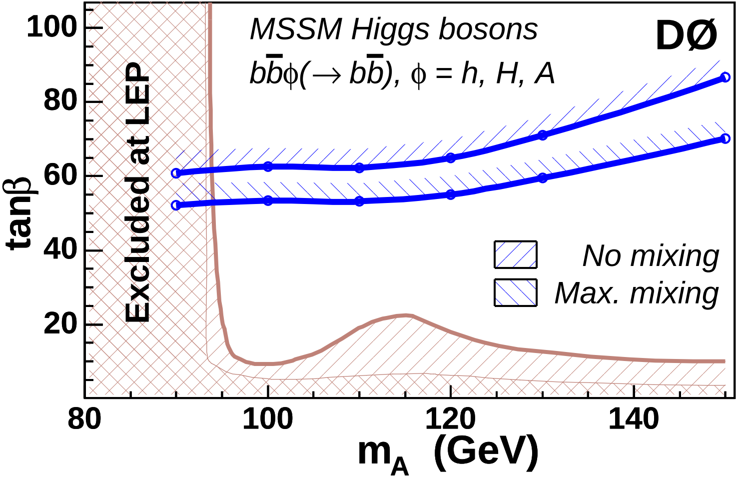

$\alpha_s(\mu)\ (g_{\Phi b\bar{b}})^2\ (\overline{m}_b(\mu)\ /\ v)^2$
LO
NLO
NNLO
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
M_{h^0}
M_{H^0}
105
106
107
108
109
110
$\mu = \mu_0 / 2 = (m_b^{pole} + M_\Phi/2)/2$
$\tan(\beta) = 40$
100
110
120
130
140
150
160
Higgs Mass [GeV]

Outline



- Top quark loop is largest contribution in SM
- As tan(β) increases, bottom-quark becomes important
- Introduce bottom-quark PDFs (5FNS) for convenience
- Differential cross-sections are experimentally more useful
- We also require bottom-quark tagging

Outline



D0 Study: Phys. Rev. Lett. **95** 151801 (2005)

Resumming Higgs processes is well established

- Total cross-section resummation
- Differential cross-section resummation

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

How does one calculate a resummed Higgs p_T^Φ spectrum while imposing $p_T^b > 20$ GeV or rapidity cuts?

One-Particle Inclusive Resummation

Outline

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

- Mod. Phys. Lett. **A19** 405 (2004)
- Int. J. Mod. Phys. **A19** 1793 (2004)
- Phys. Rev. D **73** 034001 (2006)

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

$$S^2 \frac{d^2\sigma}{dT dU} = \int_{x_1^-}^{1} \frac{dx_1}{x_1} \int_0^{\hat{s}_2^+} \frac{d\hat{s}_2}{\hat{s}_2 - \hat{t} + m_b^2} \phi(x_1)\, \phi(x_2^\star(\hat{s}_2))\, \hat{s}^2 \frac{d^2\hat{\sigma}}{d\hat{t}\, d\hat{u}}$$

$$x_2^\star(\hat{s}_2) = \frac{\hat{s}_2 + m_b^2 - Q^2 - x_1(T - Q^2)}{x_1 S + U - Q^2}$$

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

- We can expand this to NLO-NLL

$$d\hat{\sigma}^{(1)} = d\hat{\sigma}^{\mathrm{B}} \frac{\alpha_s}{\pi} \left\{ c_3 \mathcal{D}_1(\hat{s}_2) + c_2 \mathcal{D}_0(\hat{s}_2) + c_1 \delta(\hat{s}_2) \right\}$$

- This is compared to NLO fixed-order results
- Expand onto higher orders...

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

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- This is compared to NLO fixed-order results
- Expand onto higher orders...

$$d\hat{\sigma}^{(2)} = d\hat{\sigma}^{B}\frac{\alpha_s^2}{\pi^2}\Bigg\{\frac{1}{2}c_3^2\mathcal{D}_3(\hat{s}_2) + \left[\frac{3}{2}c_3\,c_2 - \frac{\beta_0}{4}c_3\right]\mathcal{D}_2(\hat{s}_2)$$

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

$$\left. + \frac{\beta_0}{4}c_3\ln\left(\frac{\mu_R^2}{Q^2}\right) - \zeta_2\,c_3^2\right]\mathcal{D}_1(\hat{s}_2) + \left[-(C_F + C_A)\ln\left(\frac{\mu_F^2}{Q^2}\right)c_1\right.$$

$$- \frac{\beta_0}{4}(C_F + C_A)\ln\left(\frac{\mu_F^2}{Q^2}\right)\ln\left(\frac{\mu_R^2}{Q^2}\right) + (C_F + C_A)\frac{\beta_0}{8}\ln^2\left(\frac{\mu_F^2}{Q^2}\right)$$

$$\left. - \zeta_2\,c_2\,c_3 + \zeta_3\,c_3^2\right]\mathcal{D}_0(\hat{s}_2)\Bigg\}$$

$$d\hat{\sigma}^{(3)} = d\hat{\sigma}^{B}\frac{\alpha_s^3}{\pi^3}\Big\{\cdots\Big\}$$

$$bg \to b\Phi$$

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

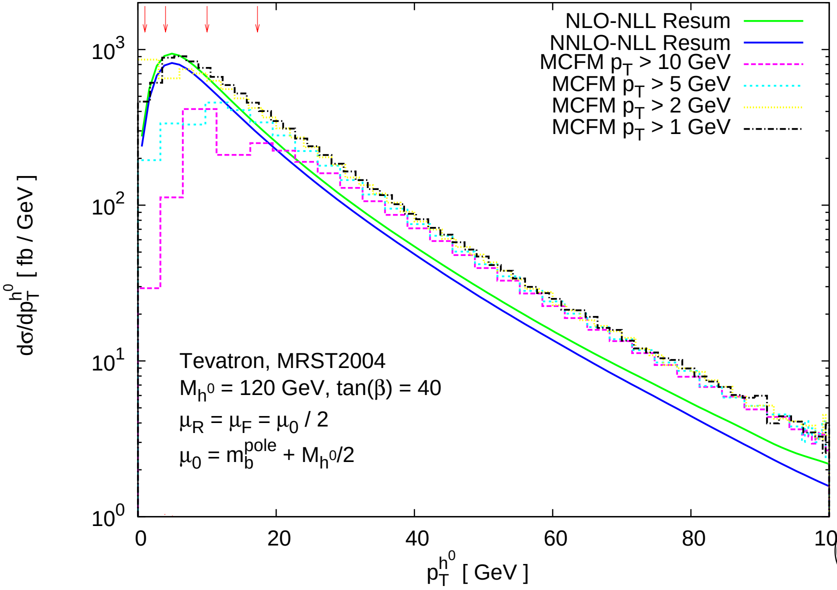
$$c_2 = 2C_F \ln\left(\frac{m_b^2 - \hat{t}}{m_b\sqrt{\hat{s}}}\right) + C_A \ln\left(\frac{m_b^2 - \hat{u}}{m_b^2 - \hat{t}}\right) - C_F - 2C_F \ln\left(\frac{Q^2 - \hat{u}}{Q^2}\right) - 2C_A \ln\left(\frac{Q^2 - \hat{t}}{Q^2}\right) - (C_F + C_A) \ln\left(\frac{\mu_F^2}{\hat{s}}\right)$$

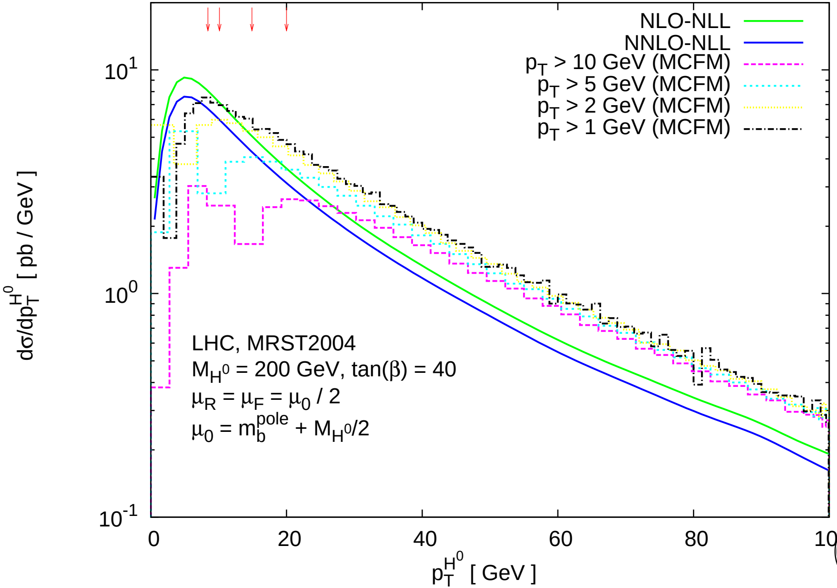
$$c_3 = 2(C_A + C_F)$$

First checked the behavior versus fixed-order NLO calculations

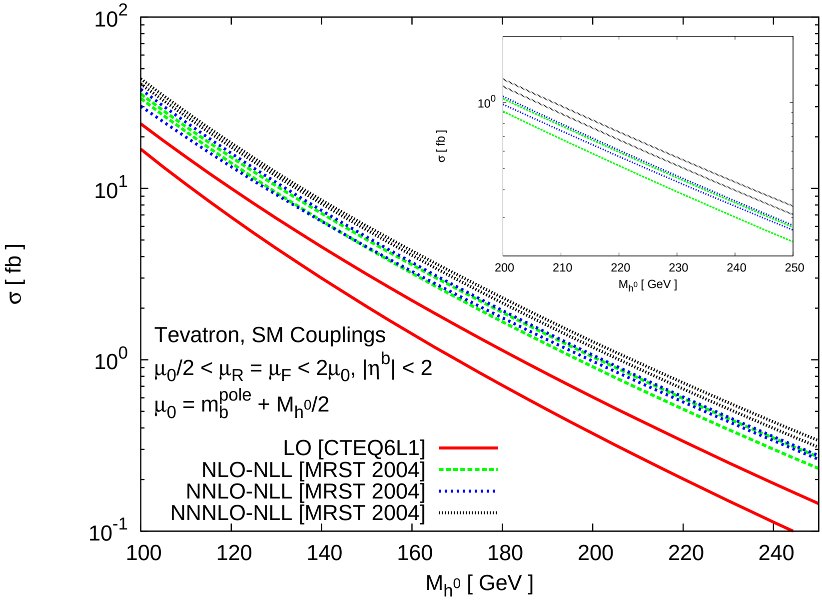
- Use the same parameters as other published fixed-order calculations
  - $M_{h^0} = 120$ GeV, $M_{H^0} = 200$ GeV
  - $p_T^b > 20$ GeV, $|\eta^b| < 2$ (2.5)
  - $\tan(\beta) = 40$
  - $\mu = \mu_0/2$, $\mu_0 = m_b^{\text{pole}} + M_\Phi/2$
  - Bottom-quark $\overline{\text{MS}}$ running mass
- Then we can study other aspects
  - μ-dependence
  - Additional differential quantities
  - Total cross-sections, etc

Outline

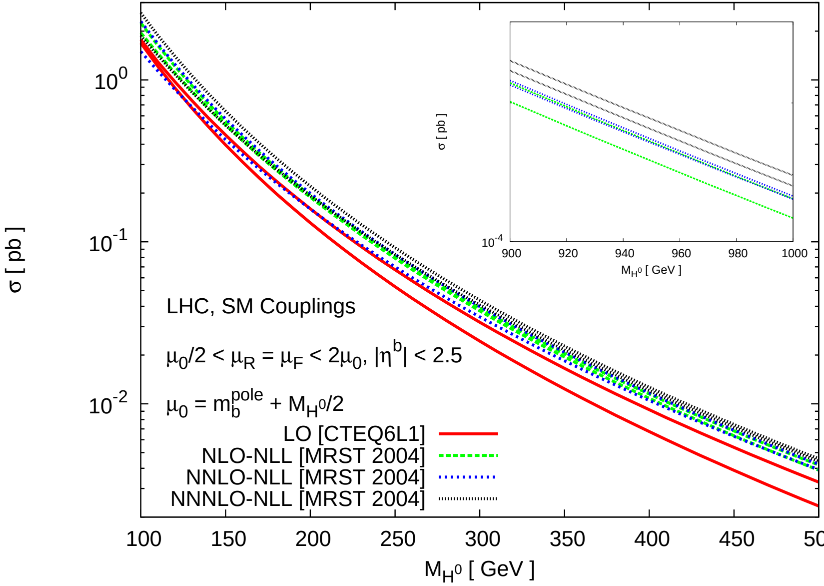

NLO-NLL Resum
NNLO-NLL Resum
MCFM pT > 10 GeV
MCFM pT > 5 GeV
MCFM pT > 2 GeV
MCFM pT > 1 GeV
Tevatron, MRST2004
Mh0 = 120 GeV, tan(β) = 40
μR = μF = μ0 / 2
μ0 = mbpole + Mh0/2
dσ/dpTh0 [fb / GeV]
pTh0 [GeV]
10^3
10^2
10^1
10^0
0
20
40
60
80
100


NLO-NLL
NNLO-NLL
pT > 10 GeV (MCFM)
pT > 5 GeV (MCFM)
pT > 2 GeV (MCFM)
pT > 1 GeV (MCFM)
LHC, MRST2004
M_{H^0} = 200 GeV, tan(β) = 40
$\mu_R = \mu_F = \mu_0 / 2$
$\mu_0 = m_b^{pole} + M_{H^0}/2$
$d\sigma/dp_T^{H^0}$ [pb / GeV]
$p_T^{H^0}$ [GeV]
10^1
10^0
10^{-1}
0
20
40
60
80
100

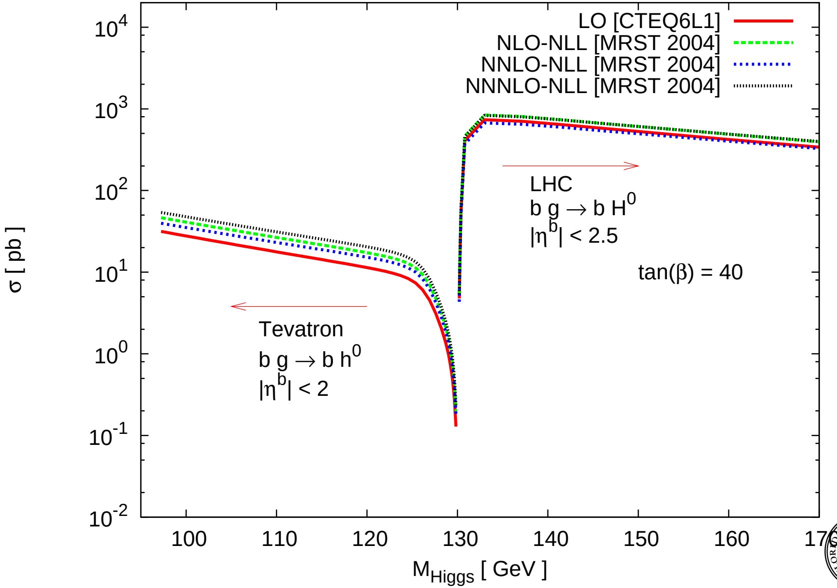
Outline



σ [fb]
10^2
10^1
10^0
10^{-1}
100
120
140
160
180
200
220
240
M_{h^0} [GeV]
Tevatron, SM Couplings
$\mu_0/2 < \mu_R = \mu_F < 2\mu_0$, $|\eta^b| < 2$
$\mu_0 = m_b^{pole} + M_{h^0}/2$
LO [CTEQ6L1]
NLO-NLL [MRST 2004]
NNLO-NLL [MRST 2004]
NNNLO-NLL [MRST 2004]
σ [fb]
10^0
200
210
220
230
240
250
M_{h^0} [GeV]

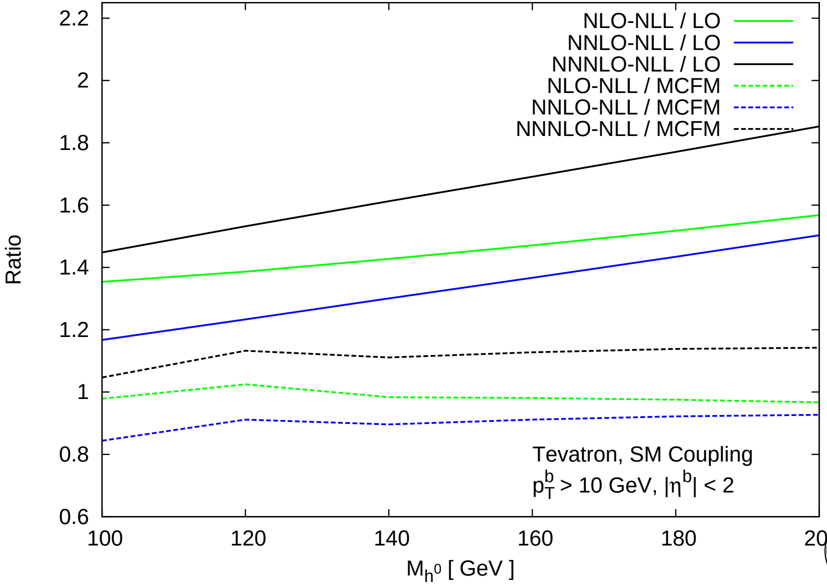

σ [pb]
10^0
10^-1
10^-2
100
150
200
250
300
350
400
450
500
M_H0 [GeV]
LHC, SM Couplings
μ_0/2 < μ_R = μ_F < 2μ_0, |η^b| < 2.5
μ_0 = m_b^pole + M_H0/2
LO [CTEQ6L1]
NLO-NLL [MRST 2004]
NNLO-NLL [MRST 2004]
NNNLO-NLL [MRST 2004]
σ [pb]
10^-4
900
920
940
960
980
1000
M_H0 [GeV]

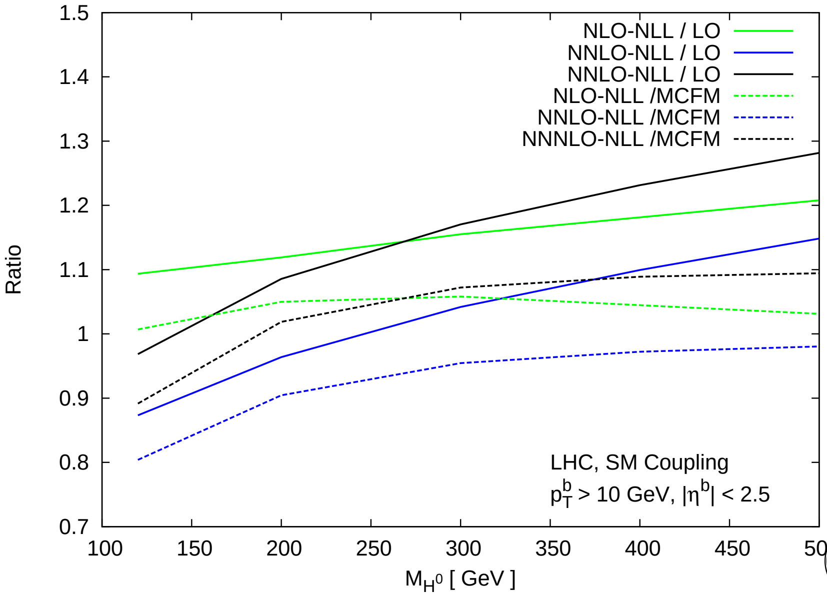
Outline


LO [CTEQ6L1]
NLO-NLL [MRST 2004]
NNLO-NLL [MRST 2004]
NNNLO-NLL [MRST 2004]
LHC
b g → b H^0
|η^b| < 2.5
tan(β) = 40
Tevatron
b g → b h^0
|η^b| < 2
σ [pb]
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
100
110
120
130
140
150
160
170
M_Higgs [GeV]

Summary

- 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


NLO-NLL / LO
NNLO-NLL / LO
NNNLO-NLL / LO
NLO-NLL / MCFM
NNLO-NLL / MCFM
NNNLO-NLL / MCFM
Ratio
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
100
120
140
160
180
200
M_{h^0} [GeV]
Tevatron, SM Coupling
p_T^b > 10 GeV, |η^b| < 2



NLO-NLL / LO
NNLO-NLL / LO
NNLO-NLL / LO
NLO-NLL /MCFM
NNLO-NLL /MCFM
NNNLO-NLL /MCFM
LHC, SM Coupling
$p_T^b > 10$ GeV, $|\eta^b| < 2.5$
Ratio
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
100
150
200
250
300
350
400
450
500
M_{H^0} [GeV]