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

Bryan J. Field

in association with L. Reina (FSU) and C. Jackson (BNL)

Florida State University

2006 Joint Meeting of Pacific Region Particle Physics Communities

30 October 2006

Outline

- Introduction
  - Quick review of SM and MSSM
  - Production channels and problems
  - $bg \to b\Phi \;\; \Phi = \{h^0, H^0\}$
- Limits on $\tan(\beta)$ from Higgs physics
- Fixed-order and Resummation
  - Small transverse momentum (p_T)
  - Formalism for $2 \to 2$ 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

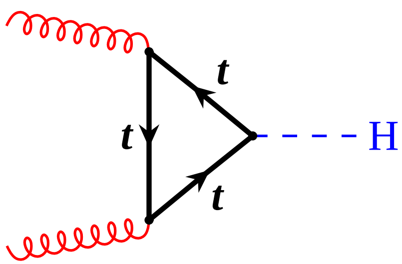
$$\text{EWSB}: h^{\text{SM}} \rightarrow \{h^0, H^0, H^\pm, A^0\} \qquad \tan(\beta) = v_2/v_1$$

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

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

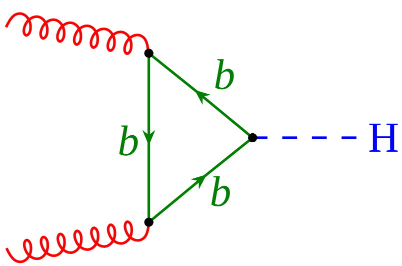
How to make a Higgs

- Higgs couples to mass
- Top quark loop is largest contribution in SM
- Several groups have calculated fixed-order cross-sections to NNLO
  - R. Harlander and W. Kilgore [Phys. Rev. Lett. **88** 201801 (2002)]
  - C. Anastasiou and K. Melnikov [Nucl. Phys. **B646** 220 (2002)]
  - V. Ravindran, J. Smith, and W. van Neerven [Nucl. Phys. **B665** 325 (2003)]
  - C. Anastasiou, K. Melnikov, F. Petriello [Phys. Rev. Lett. **93** 262002 (2004)]



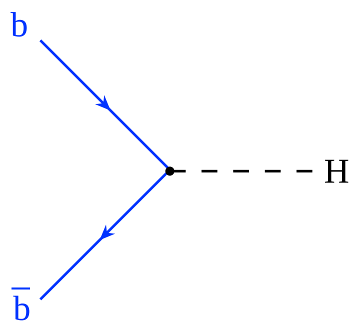
How to make a Higgs

- In MSSM, this is not always true
- As $\tan(\beta)$ increases, bottom-quark becomes important
- Both top- and bottom-quarks can be important
  - BJF, S. Dawson, and J. Smith [Phys. Rev. D **69** 074013 (2004)]
  - S. Dawson, C. Jackson, L. Reina, and D. Wackeroth [Mod. Phys. Lett. **A21** 89 (2006)]



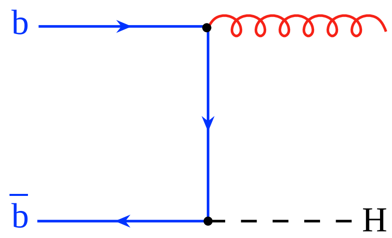
How to make a Higgs

- We are interested in bottom-quarks
- Introduce bottom-quark PDFs (5FNS) for convenience
- Potentially large signal in MSSM at large values of $\tan(\beta)$
- 5FNS allows a study of lower order diagrams
  - R. Harlander and W. Kilgore [Phys. Rev. D **68** 013001 (2003)]
  - F. Maltoni, Z. Sullivan, and S. Willenbrock [Phys. Rev. D **67** 093005 (2003)]



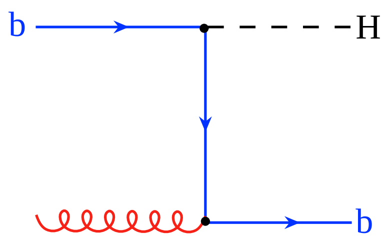
How to make a Higgs

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



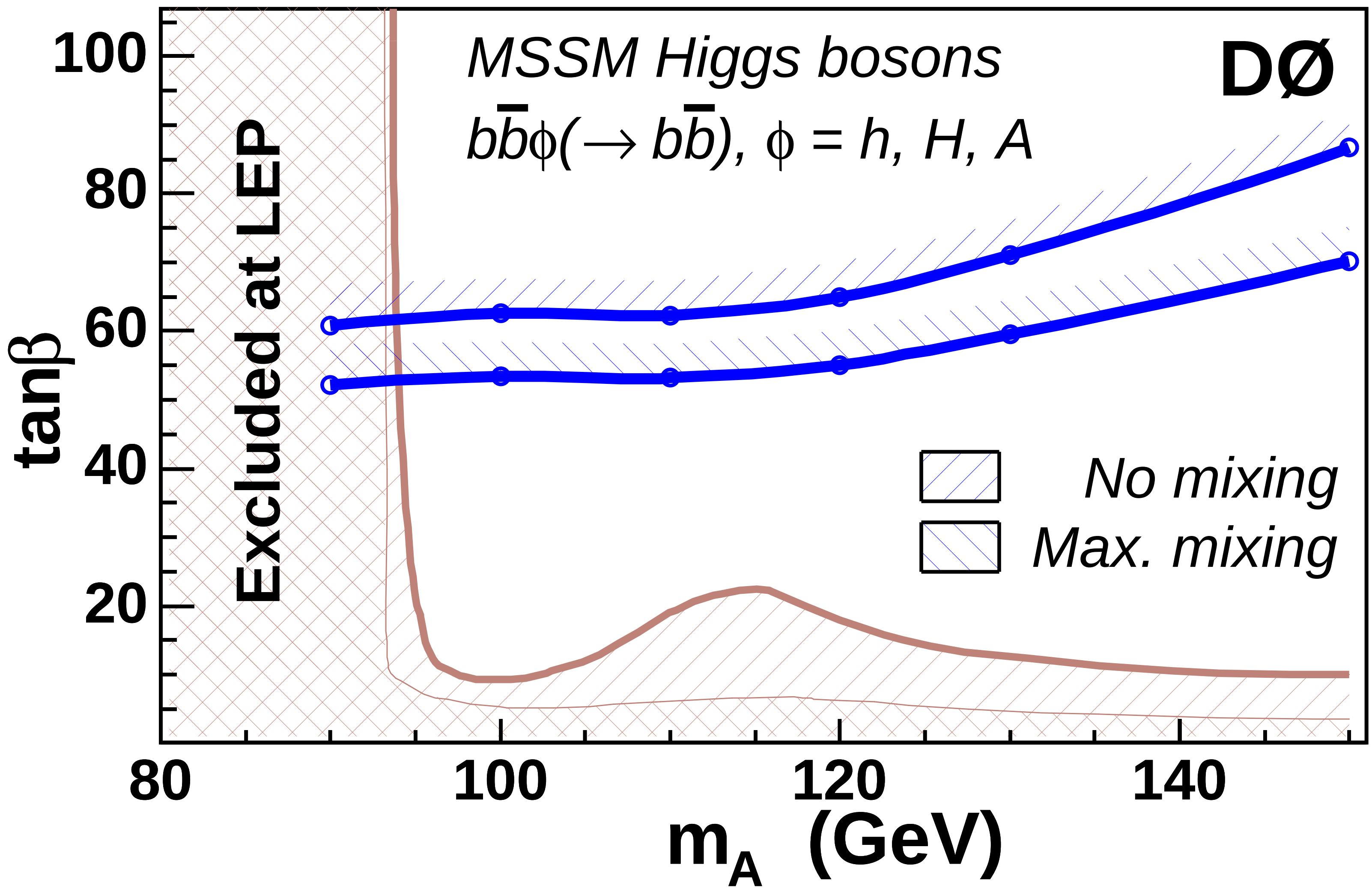
How to make a Higgs

- We also require bottom-quark tagging
- This is our process in 5FNS
  - J. Campbell, R.K. Ellis, F. Maltoni, and S. Willenbrock [Phys. Rev. D **67** 095002 (2003)]
  - S. Dawson, C.B. Jackson, L. Reina, and D. Wackeroth [Phys. Rev. Lett. **94** 031802 (2005)]
- $bg \to b\Phi$ is a preferred study, fixed-order calculations have been completed
- An experimental limit had been set with this process



Limits on $\tan(\beta)$

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



Our Study

- 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 $bg \longrightarrow b\Phi \; \Phi = \{h^0, H^0\}$
  - 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
  - C.P. Yuan [Phys. Lett. B **283** 395 (1992)]
  - 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)]
  - A. Kulesza, G. Sterman, and W. Vogelsang [Phys. Rev. D **69** 014012 (2004)]
- Differential cross-section resummation
  - E. Berger and J-W. Qiu [Phys. Rev.D **67** 034026 (2003)]
  - BJF [Phys. Rev. D **70** 054008 (2004)]
  - G. Bozzi, S. Catani, D. de Florian, and M. Grazzini [Nucl. Phys. B **737** 73 (2006)]

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?

1PI Resummation

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

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

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

NLL and NNLL

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

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

$$d\hat{\sigma}^{(2)} = d\hat{\sigma}^{\mathsf{B}} \frac{\alpha_s^2}{\pi^2} \left\{ \frac{1}{2} c_3^2 \mathcal{D}_3(\hat{s}_2) + \left[\frac{3}{2} c_3\, c_2 - \frac{\beta_0}{4} c_3\right] \mathcal{D}_2(\hat{s}_2) \right.$$
$$+ \left[c_3\, c_1 + (C_F + C_A)^2 \ln^2\left(\frac{\mu_F^2}{Q^2}\right) - 2(C_F + C_A) T_2 \ln\left(\frac{\mu_F^2}{Q^2}\right) \right.$$
$$\left. + \frac{\beta_0}{4} c_3 \ln\left(\frac{\mu_R^2}{Q^2}\right) - \zeta_2\, c_3^2 \right] \mathcal{D}_1(\hat{s}_2) + \left[-(C_F + C_A) \ln\left(\frac{\mu_F^2}{Q^2}\right) c_1 - \frac{\beta_0}{4} (C_F + \right.$$
$$\left.\left. C_A) \ln\left(\frac{\mu_F^2}{Q^2}\right) \ln\left(\frac{\mu_R^2}{Q^2}\right) + (C_F + C_A) \frac{\beta_0}{8} \ln^2\left(\frac{\mu_F^2}{Q^2}\right) - \zeta_2\, c_2\, c_3 + \zeta_3\, c_3^2 \right] \mathcal{D}_0(\hat{s}_2) \right\}$$

Coefficients

$$bg \longrightarrow b\Phi$$

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

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

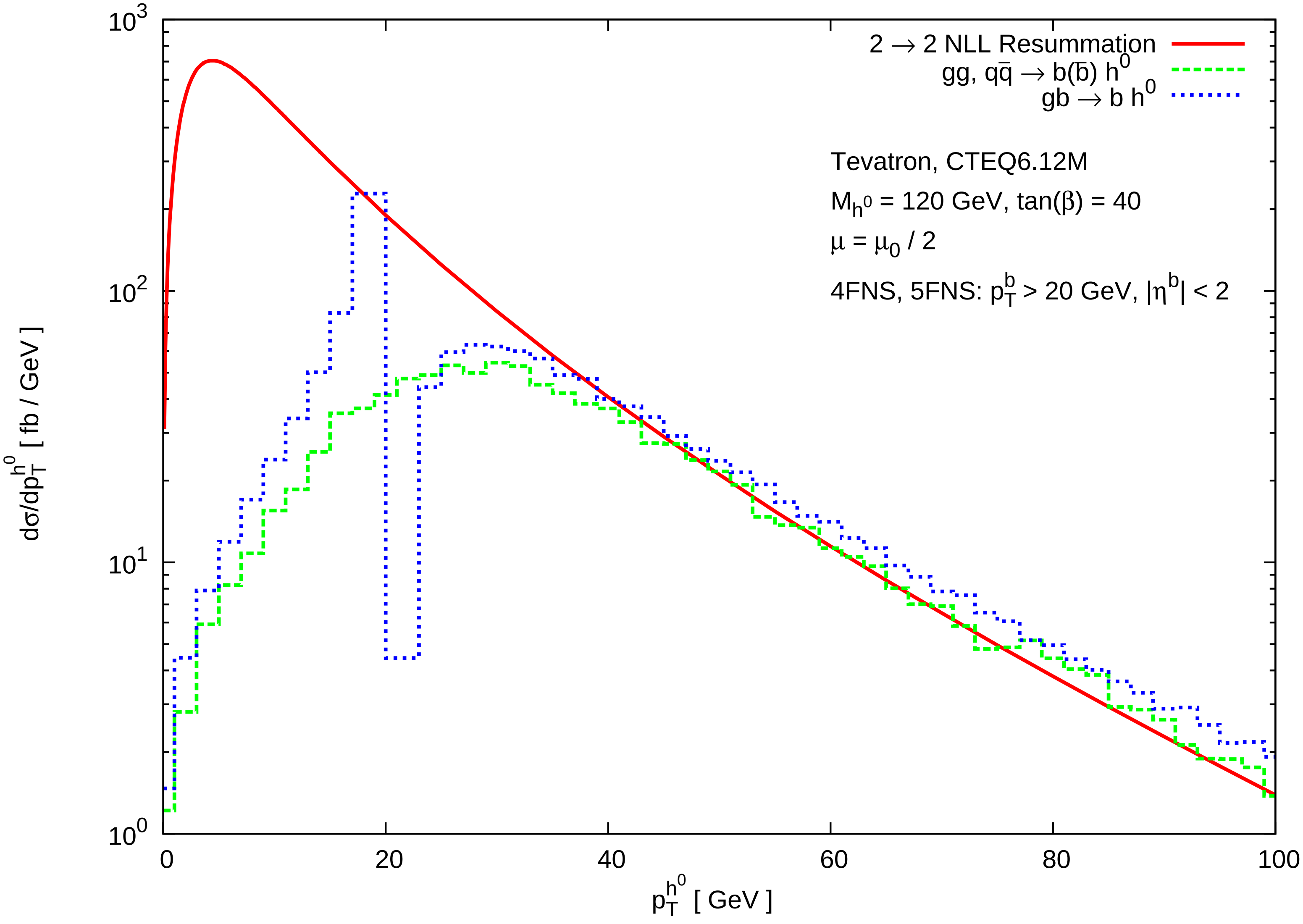
$$c_3 = 2(C_A + C_F)$$

Theoretical Checks

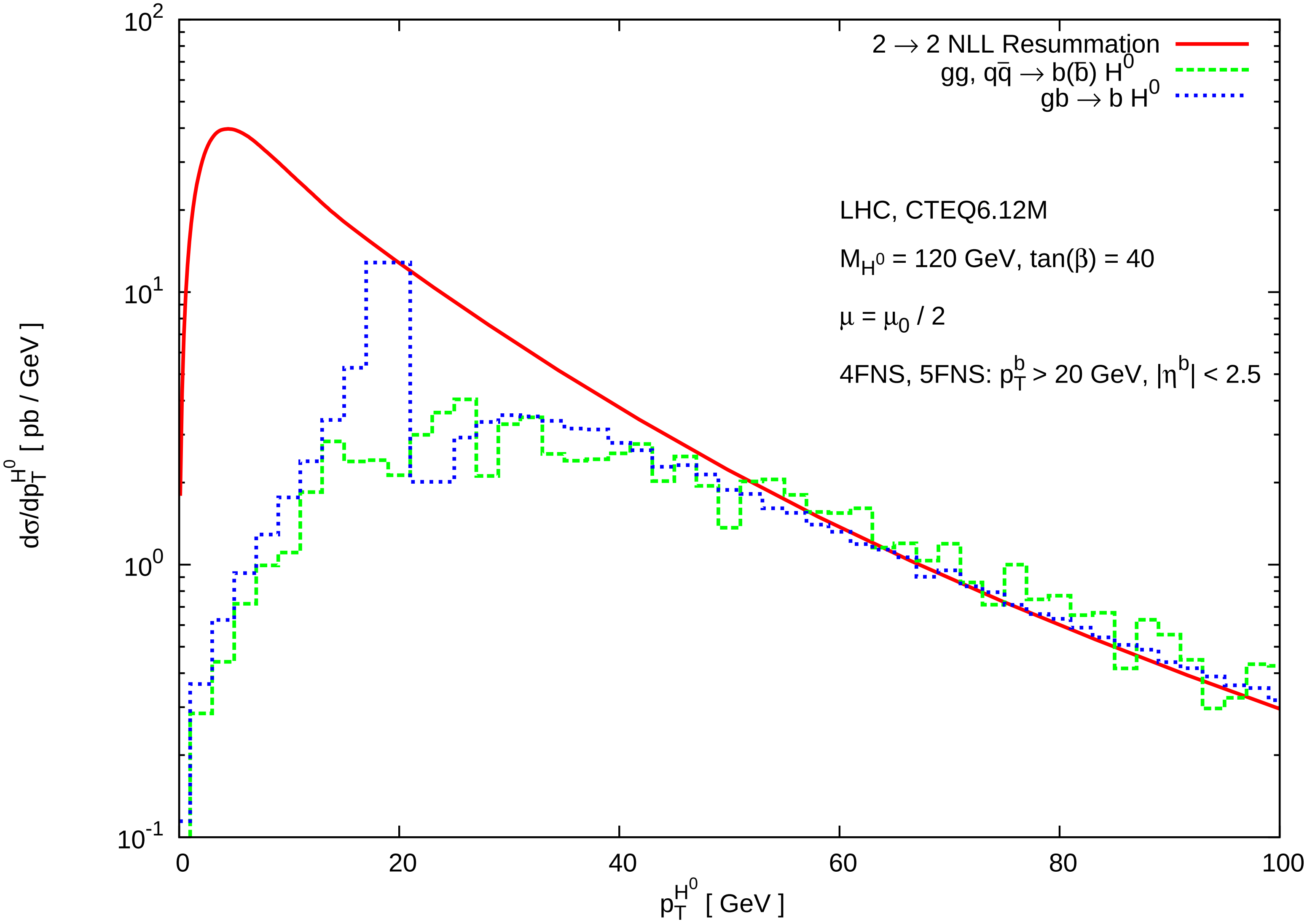
First we needed to check the small-p_T behavior of known fixed-order calculations

- 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
  - μ-dependence
  - Additional differential quantities
  - Total cross-sections, etc

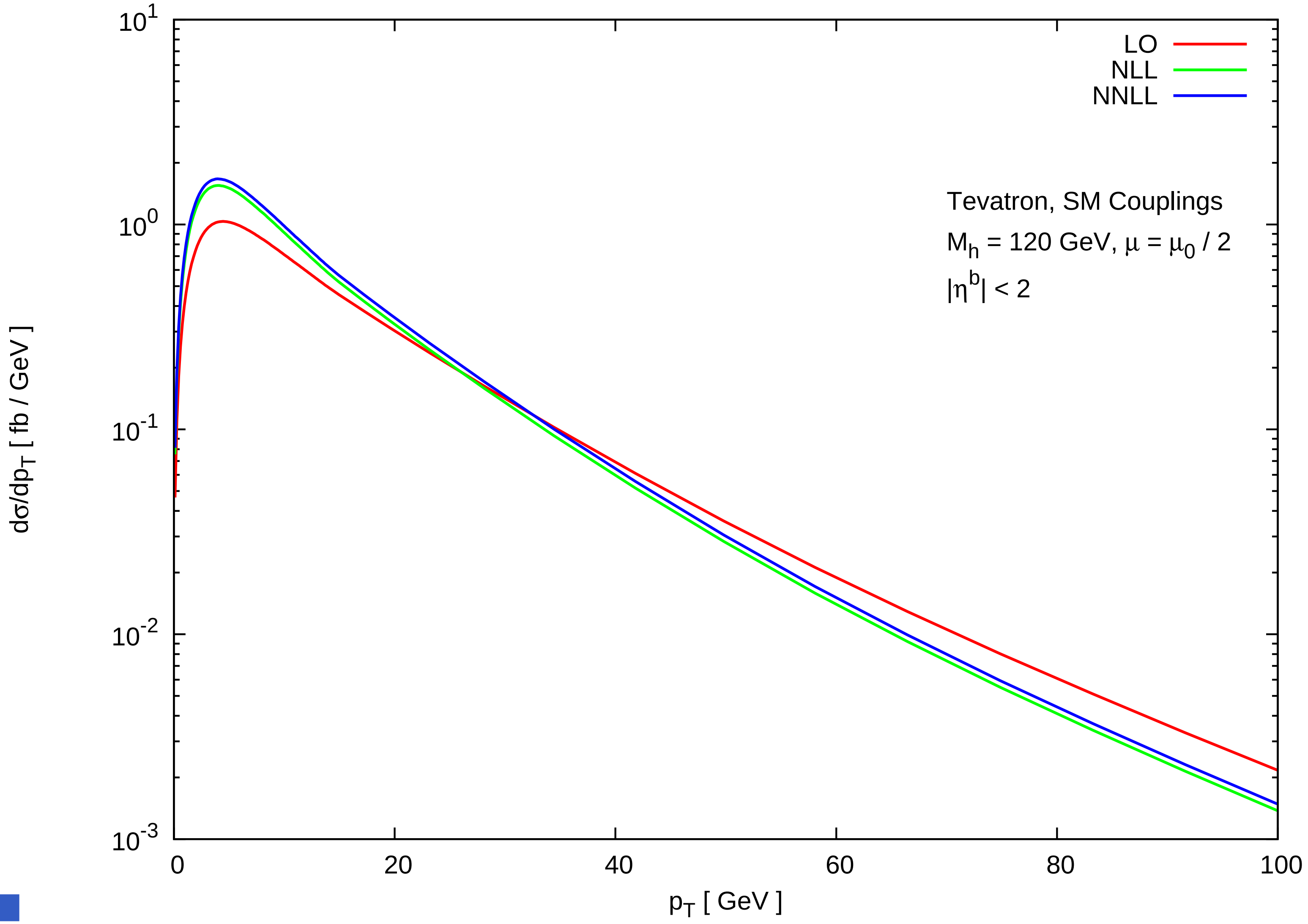
NLL Resummation Results



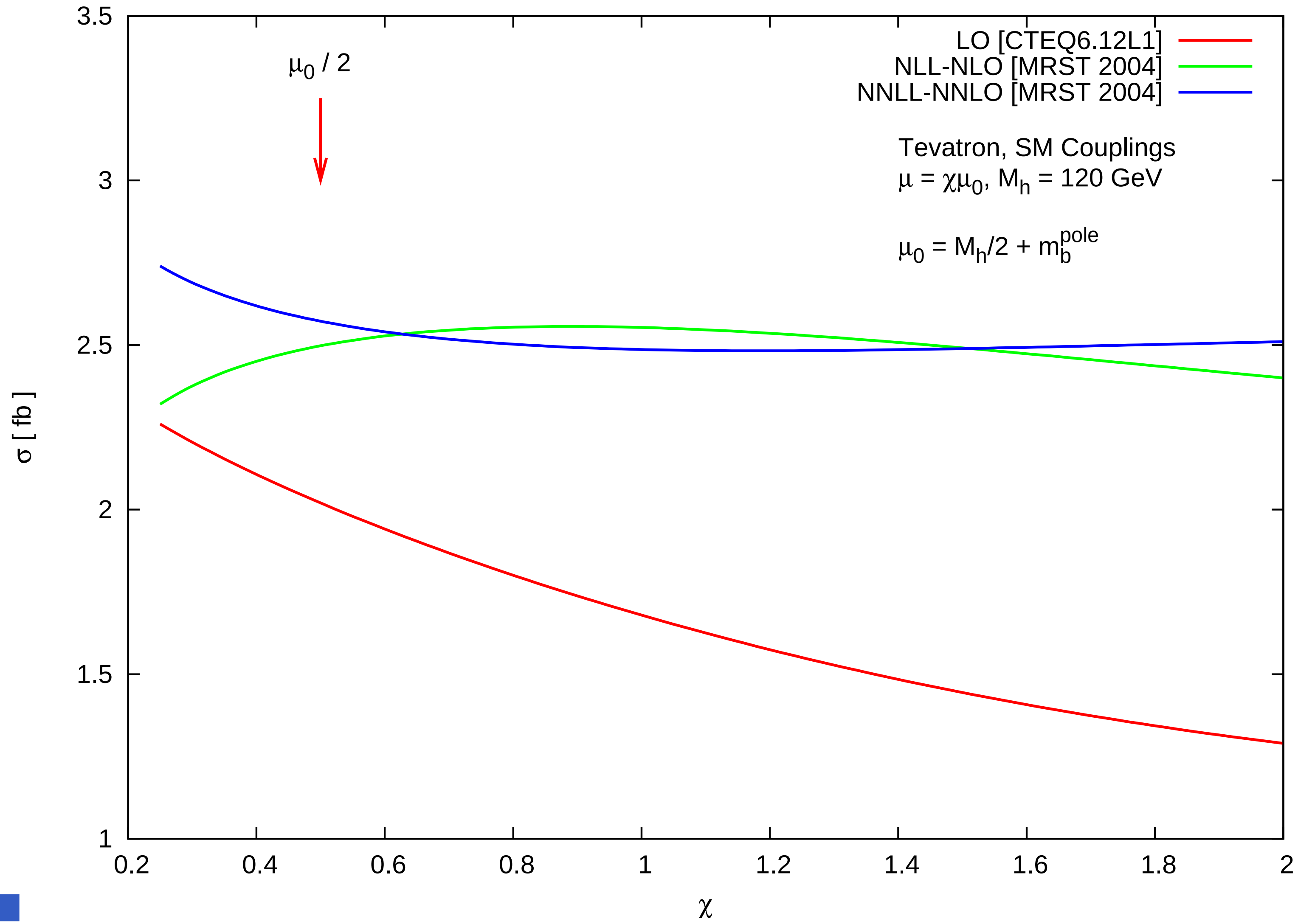
NLL Resummation Results



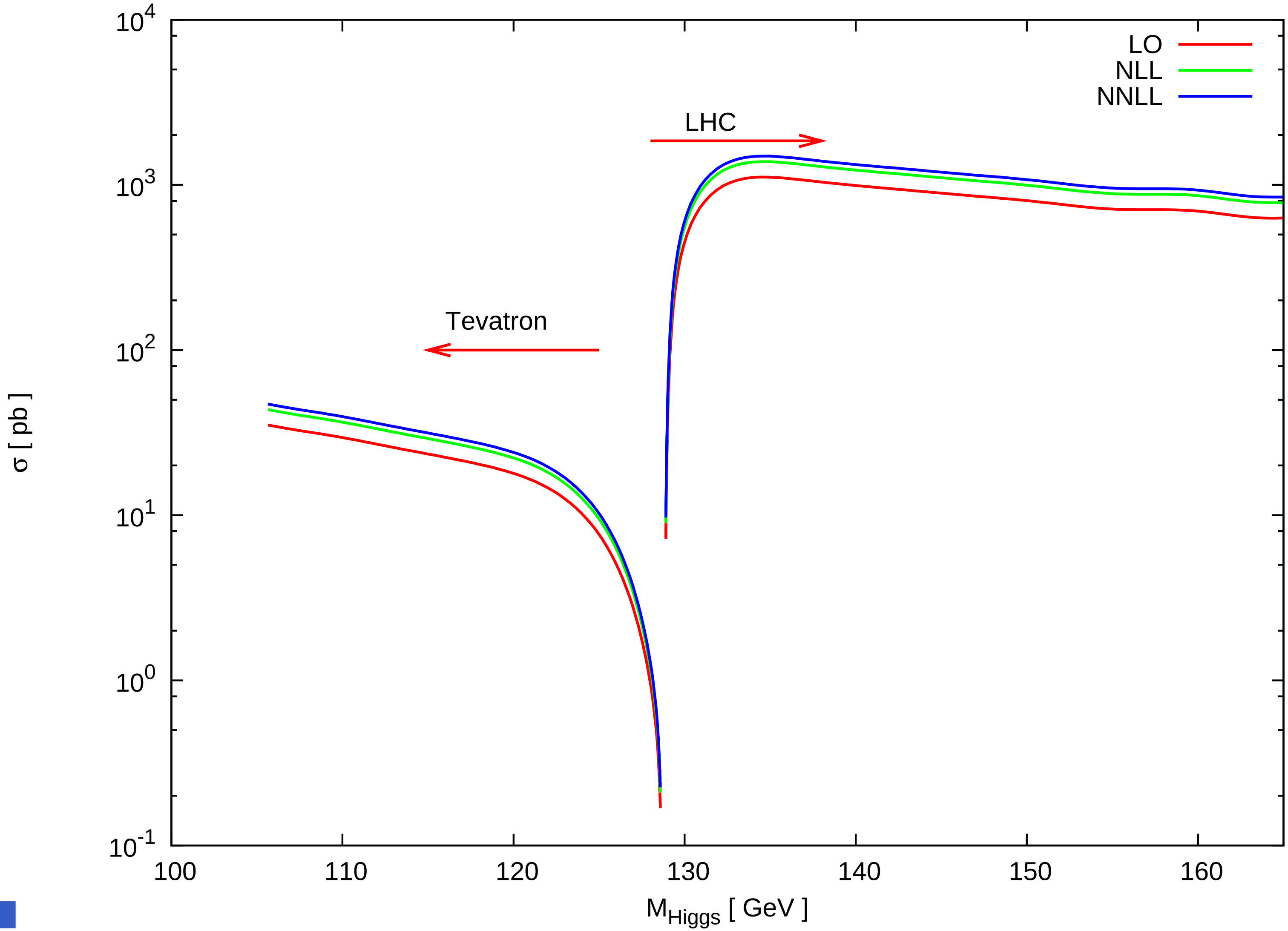
Resummation Results at NNLL



μ Dependence



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