Higgs Boson Production with b quarks

William Kilgore
Brookhaven National Laboratory
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Introduction

There has been a lot of work over the past decade on Higgs boson production via the coupling to b quarks.

- gg → bbH @NLO [Dawson, et al.],[Dittmaier, et al.]
- bb → H/A @NNLO [Harlander and WK]
- bg → bH @NLO [Ellis, et al.]
- 1-loop SUSY QCD and EW corrections to bbϕ couplings [Dittmaier, et al.]
- 2-loop SUSY QCD corrections to bbϕ couplings [Noth and Spira]

Why so much interest? … SUSY!

Standard Model Higgs

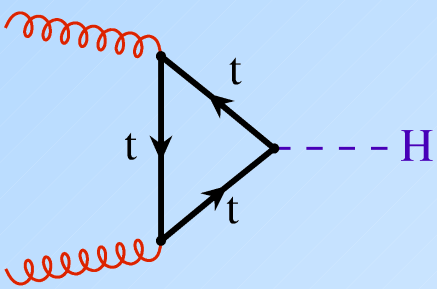
In the Standard Model, there is a single Higgs doublet which breaks electroweak symmetry, leaving one Higgs Boson and giving mass to the $W^\pm$ and Z bosons and to the quarks and leptons. The couplings are proportional to the masses

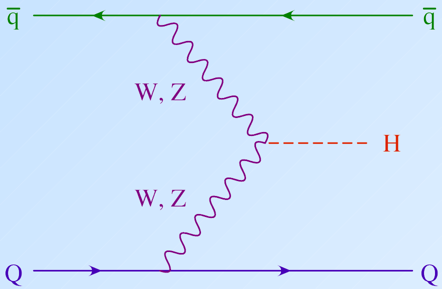
$$g_{WWH} = 2M_W/v \qquad g_{ZZH} = 2M_Z/v$$

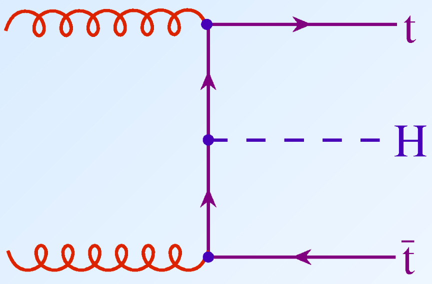
$$g_{t\bar{t}H} = \sqrt{2}m_t/v \qquad g_{b\bar{b}H} = \sqrt{2}m_b/v$$

Standard Model Higgs Boson Production

In the Standard Model, Higgs production is dominated by $W^{\pm}$, Z and t processes.

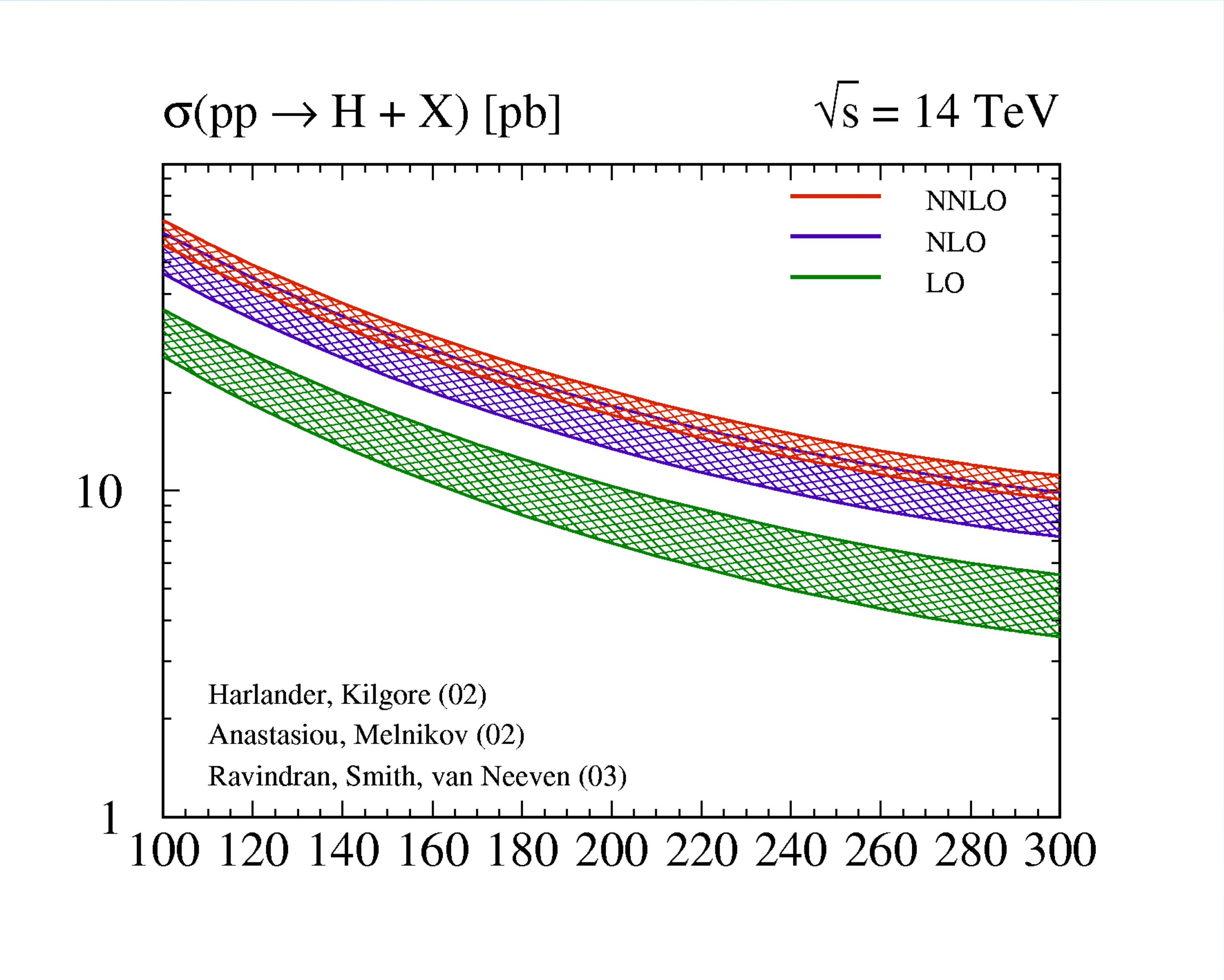






Inclusive gg→H+X

Radiative Corrections are very important



Supersymmetric Higgs Boson Production

Everything changes in Supersymmetry.

In the Minimal Supersymmetric Standard Model (MSSM) there are two Higgs doublets, H_u and H_d, with vacuum expectation values v_u, v_d, that give mass to up and down type quarks. After symmetry breaking, there are 5 physical Higgs Scalars:

$$h^0,\ H^0,\ A^0,\ H^\pm$$

which are mixtures of states from the two doublets.

Altered Couplings

The couplings MSSM Higgs are different from those of the Standard Model. Writing $g_{MSSM} = \xi\, g_{SM}$, the tree-level couplings are:

ξ	t	b	W/Z
h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\alpha-\beta)$
H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\alpha-\beta)$
A	$\cot\beta$	$\tan\beta$	0

where α is the mixing angle between h and H and $\tan\beta \equiv v_u/v_d$. In the "decoupling limit", h is Standard Model-like and $\sin\alpha \rightarrow -\cos\beta$.

H/A Couplings

For the pseudoscalar (and for H^0 in the decoupling limit) the couplings to "up-type" fermions are suppressed by tan β while those to "down-type" fermions are enhanced by tan β. This presents a problem for gluon fusion calculations:

Since $m_t > M_H$, top triangles are not suppressed by powers of M_H, but since $m_b < M_H$, b triangles are suppressed by powers of m_b/M_H. The tan β enhancement of the power suppressed b triangles is out-weighed by the cot β suppression of the top triangles, and the $gg \rightarrow H$ cross section is reduced.

A new production mode at large tan β

The importance of b-quark couplings at large tan β suggests a new inclusive production mechanism: Higgs production in association with open b-quark production:

$$gg \to b\bar{b}H$$

This mode (σ_{bb}) can dominate at large tan β because

$$\sigma_{b\bar{b}} \sim \frac{m_b^2}{M_H^2} \tan^2\beta$$

While

$$\sigma_{gg} \sim A \cot^2\beta + B \frac{m_b^2}{M_H^2} + C \frac{m_b^4}{M_H^4} \tan^2\beta$$

The cross-over is at tan β ~ 7!

Fixed vs. Variable Flavor Number

The question arises whether one should work in the Fixed Flavor Number Scheme (FFNS) or a Variable Flavor Number Scheme (VFNS).

A FFNS has a fixed number (say 4) of "active" flavors. Heavy flavor production only occurs through gluon splitting. While well-defined, FFNS seems forced if $Q^2 \gg m_q^2$. In addition, $\ln(Q/m_q)$ terms become problematic.

A VFNS recognizes thresholds and changes the number of "active" flavors with Q^2.

FFNS vs VFNS

We are all familiar with the VFNS in the form of the CWZ scheme for the running of α_s. Near a flavor threshold, one defines a "matching scale", where $\alpha_s^{(n)}$ and $\alpha_s^{(n+1)}$ are related and a "switching scale" where one starts to use $\alpha_s^{(n+1)}$.

(Almost) No one strictly adheres to the FFNS point of view, they simply raise the switching scale far above the matching scale. This is common in heavy flavor production processes where it is questionable to consider the heavy flavor fully active.

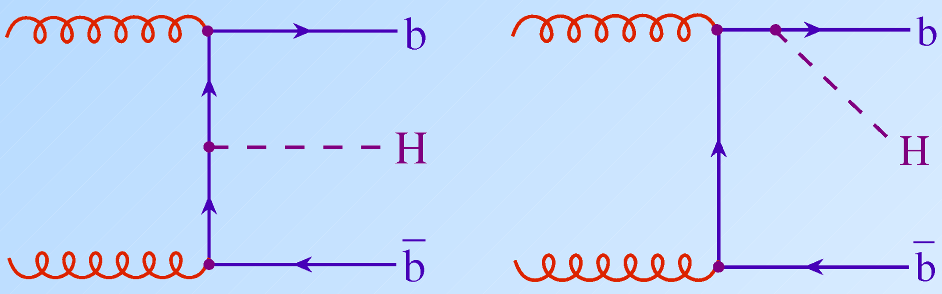
Parton Distributions in VFNS

The CWZ scheme for the running of α_s can be extended to parton distributions. Below threshold, the parton distribution is taken to vanish. At some scale (near production threshold), gluons are allowed to start splitting into heavy quark pairs. Above threshold, evolution is governed by the RGE (DGLAP).

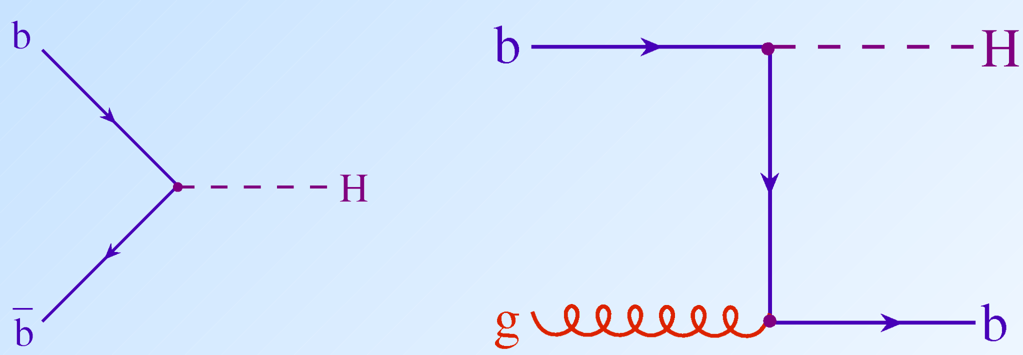
As for α_s, there is a matching scale and a switching scale that need not coincide.

Parton Distributions in VFNS

Logarithmic terms arise from forward emission of on-shell b-quarks



In VFNS, the lowest order terms are $b\bar{b}\rightarrow H$. Parton evolution resums the logarithmic terms.



VFNS: Separating the Matching and Switching scales

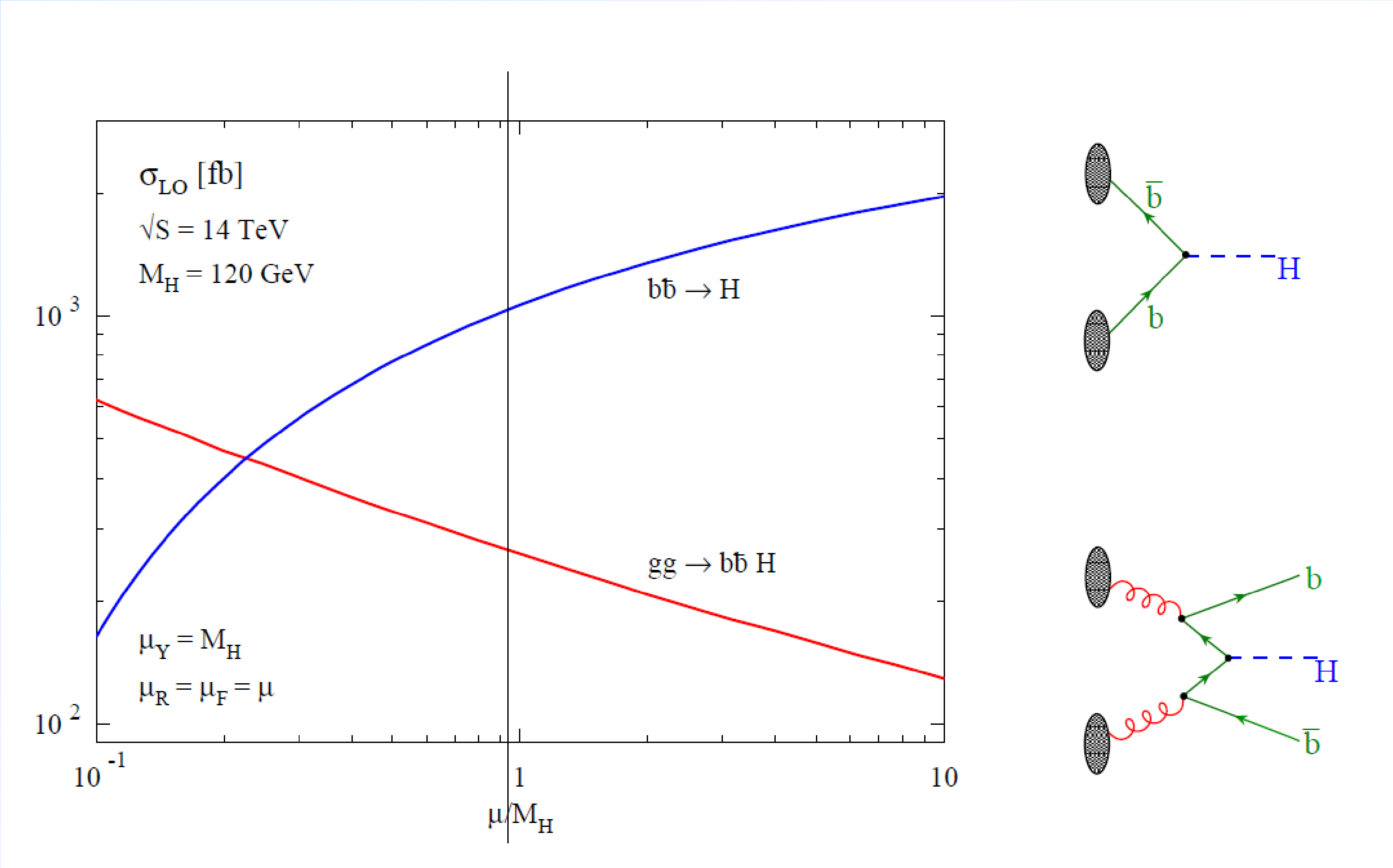
A prime motivation for separating the matching and switching scales is the worry that the transition is a crude hack of the full kinematics. This need not be the case!

Modern PDFs include the power corrections that take threshold information into account in the matching condition. ~~The effect of the power corrections rapidly evolves away~~.

Heavy quark PDFs are completely dominated by the gluon fit.

Worries about the VFNS

At leading order, the inclusive cross section for $b\bar{b} \to H$ is much bigger than $gg \to b\bar{b}H$.

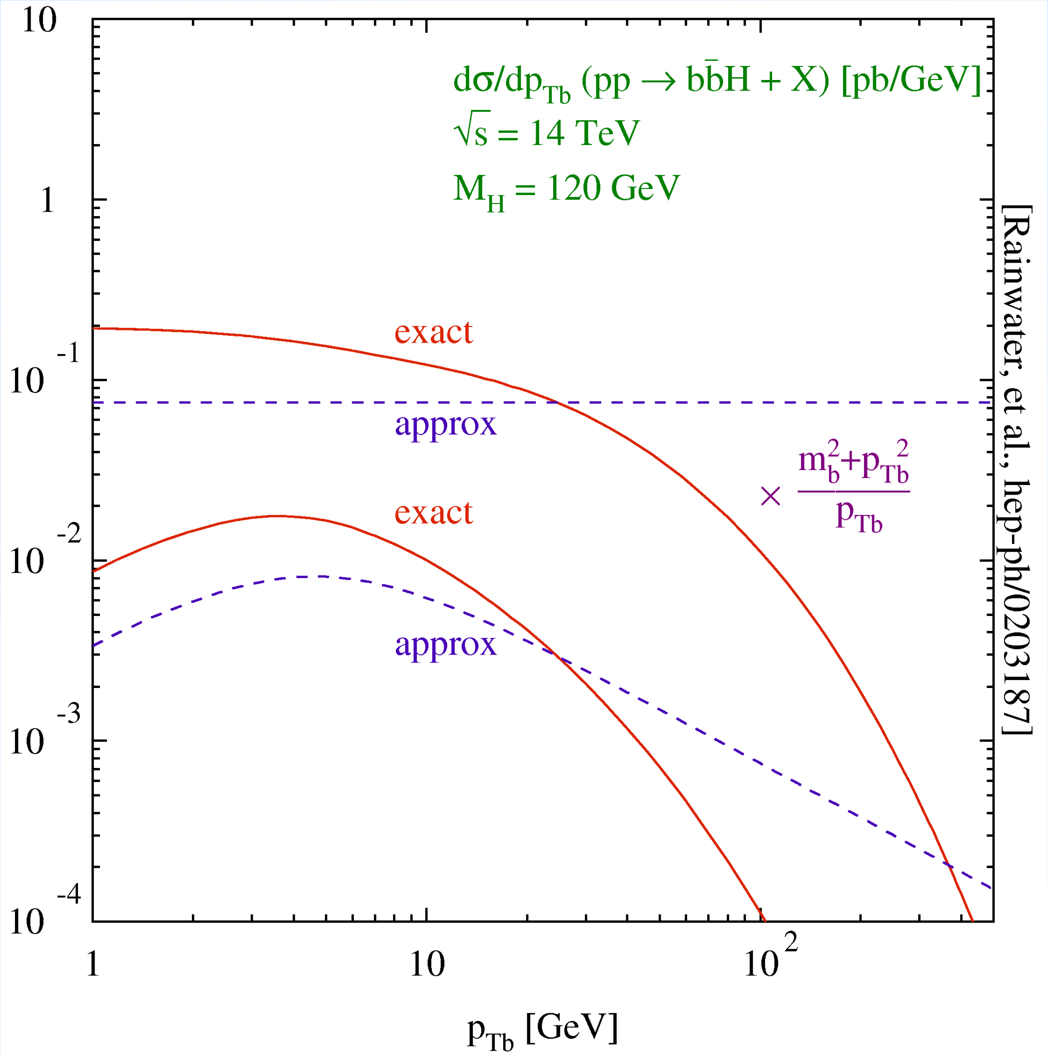


Factorization in the VFNS

This plot suggests that 14 TeV is not high enough to see full factorization of the b-quark distribution.

[Rainwater, Spira, Zeppenfeld]

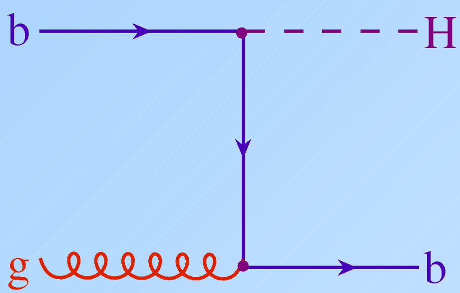
The "exact" curve is the full $\sigma(gg \to b\bar{b}H)$, while the "approximate" curve is the factorized collinear part. Proper factorization requires that the approximate term scale like $p_{Tb}/(m_b^2+p_{Tb}^2)$. Clearly the scaling falls at $\mu < M_H$.



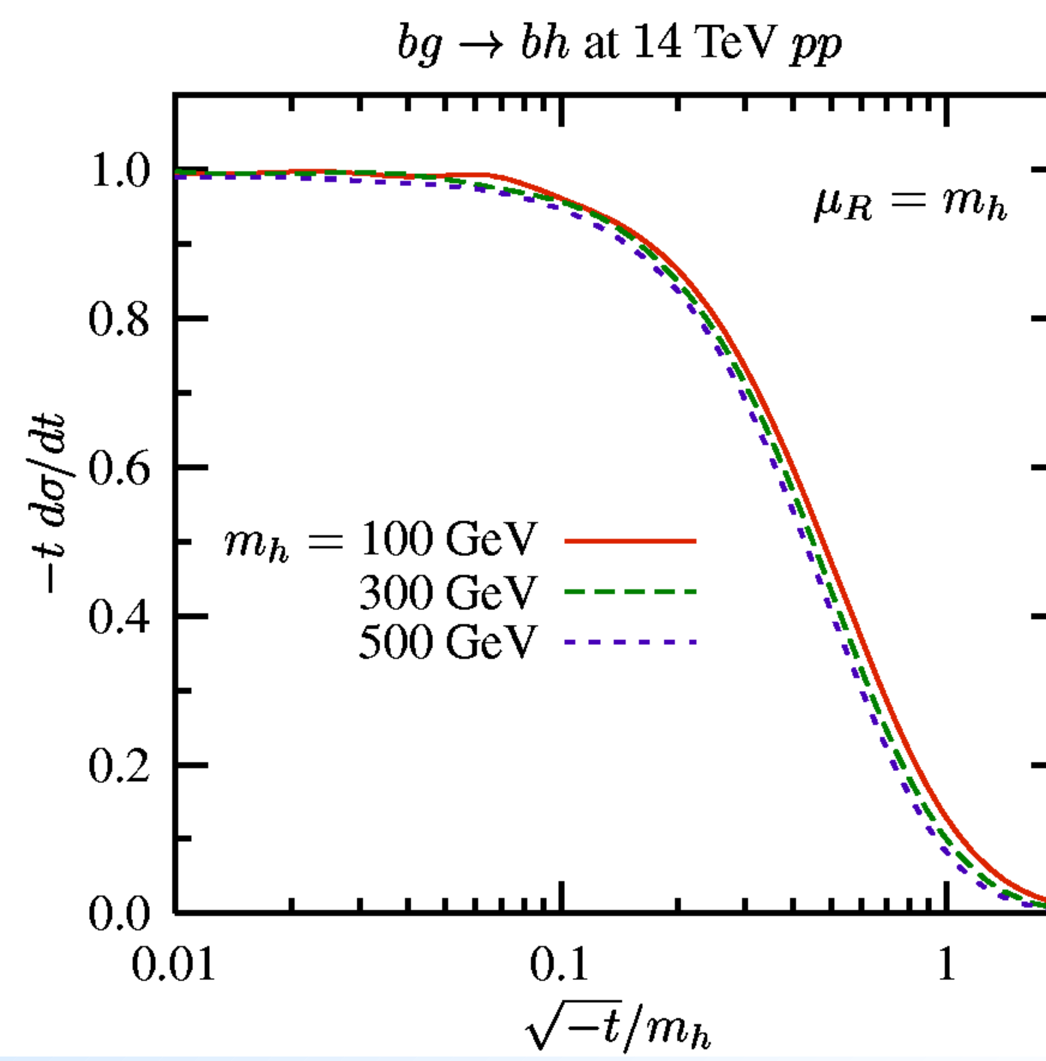
Factorization: A different spin

Another spin on this effect is that the proper factorization scale is significantly below M_H.

[Maltoni, Sullivan, Willenbrock]



The collinear enhancement is due to a t-channel pole. In the collinear region $d\sigma/dt \sim 1/t$. The collinear region ends at $t = t^*$ and the collinear log is $\ln(\sqrt{-t^*}/m_b)$. The proper factorization scale is therefore $\mu_F \sim \sqrt{-t^*}$.



[Maltoni et al., PRD67 093005]

Power Counting in the VFNS

[Dicus, Steltzer, Sullivan, Willenbrock]

The key to obtaining a consistent calculation is to properly count the powers of α_s and $\ln(M_H/m_b)$. The leading contribution in $b\bar{b}\to H$ is not order 1 but order $\alpha_s^2 \ln^2(M_H/m_b)$. To all orders in perturbation theory, the inclusive Higgs production cross section is: ($\mu_F \sim M_H$)

$$\sigma_{bb} = \sum_{n=0}^{\infty} (\alpha_s \ln(M_H/m_b))^n \{$$

$$\alpha_s^2 [c_{n0} \ln^2(M_H/m_b) + c_{n1} \ln(M_H/m_b) + c_{n2}]$$

$$+ \alpha_s^3 c_{n3} + \alpha_s^4 c_{n4} + \alpha_s^5 c_{n5} + \ldots \}$$

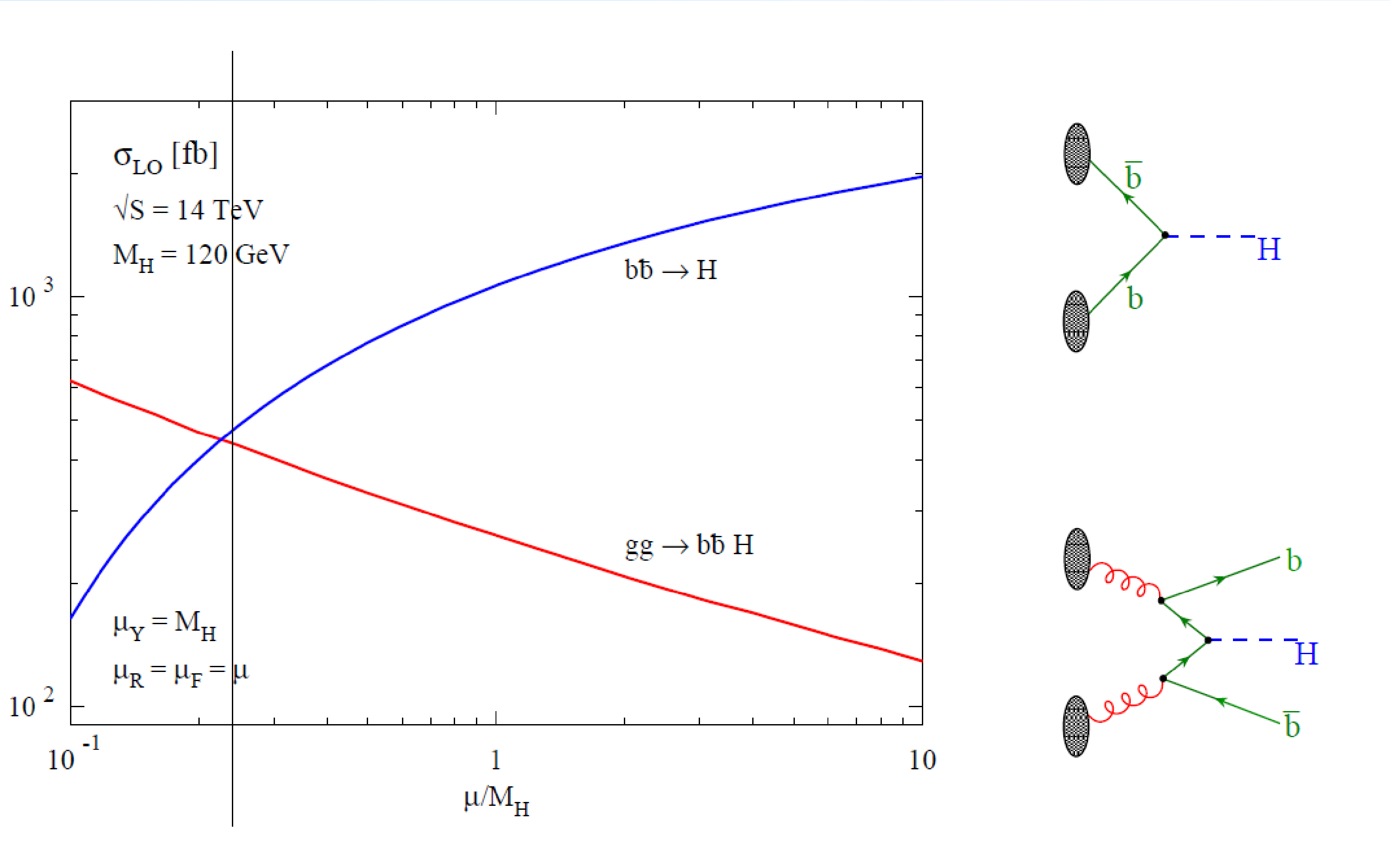
Inclusive Higgs production in VFNS

[Harlander, WK]

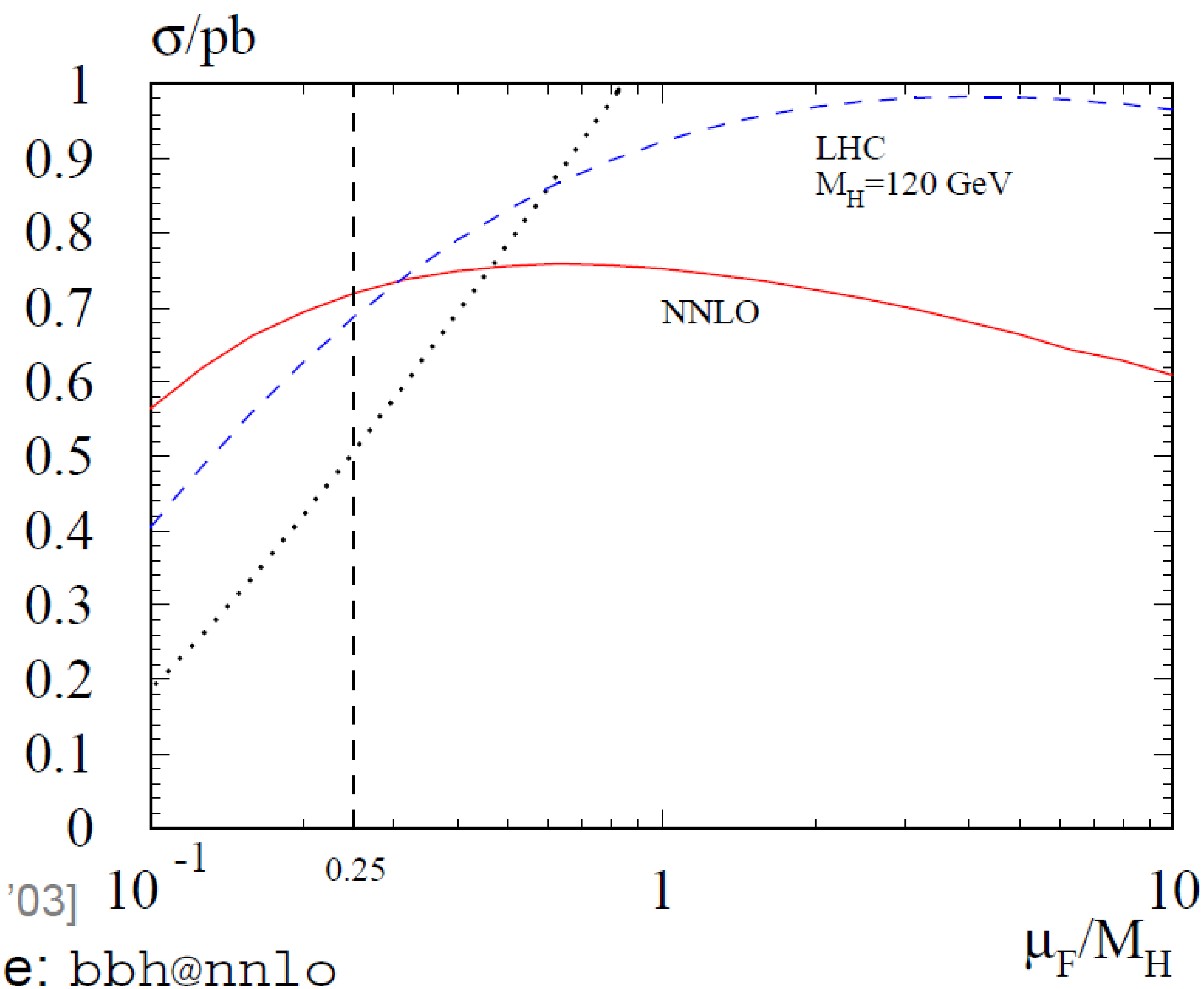
The lowest order calculation to include all terms at order α_s^2 and the resummed collinear logs is NNLO. Since all collinear logs are resummed in the PDFs, we ignore the b-quark mass in our calculation, except where it enters into the Yukawa couplings. Other b-quark mass effects are suppressed by factors of m_b^2/M_H^2.

In the $m_b \rightarrow 0$ limit, the partonic cross sections for $b\bar{b} \rightarrow H$ are identically equal to those for $b\bar{b} \rightarrow A$.

A “better” scale choice



Scale Dependence of $b\bar{b} \to H/A$ at LHC

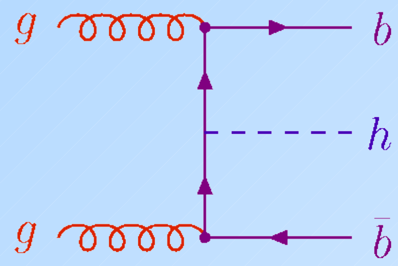


[RH, Kilgore '03]

public code: `bbh@nnlo`

Results for $gg \rightarrow b\bar{b}H$ @ NLO

Dittmaier, Krämer, Spira;   Dawson, Jackson, Reina, Wackeroth



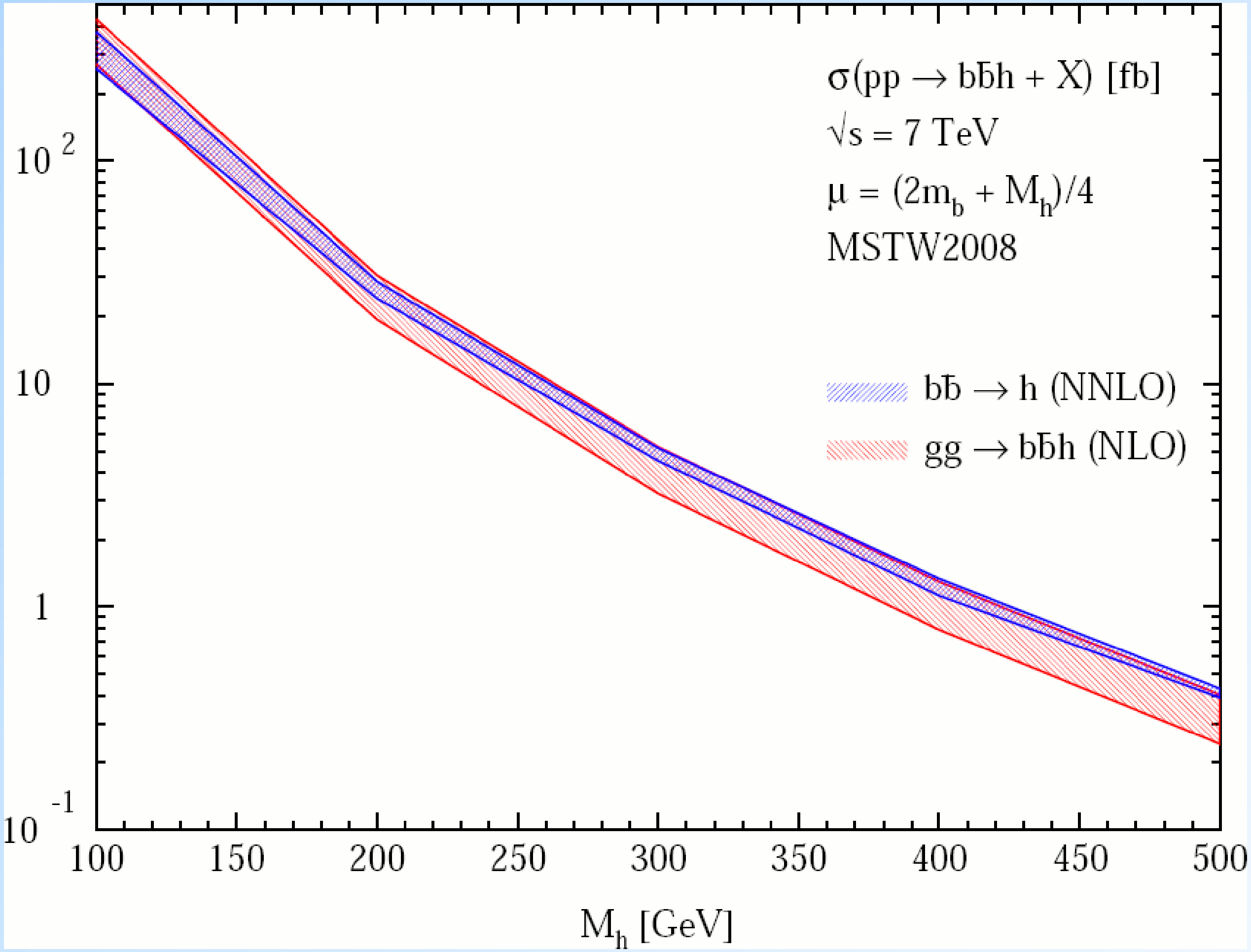
FFNS result for $pp \rightarrow b\bar{b}H$ @ NLO. This calculation goes to order α_s^3 (one order higher than the VFNS results) and includes more of the log-enhanced terms.

This result is flexible in that it can be applied to the

- Double tag mode
- Single tag mode
- Inclusive mode

But it still suffers from un-resummed log-enhanced terms in (semi-)inclusive modes.

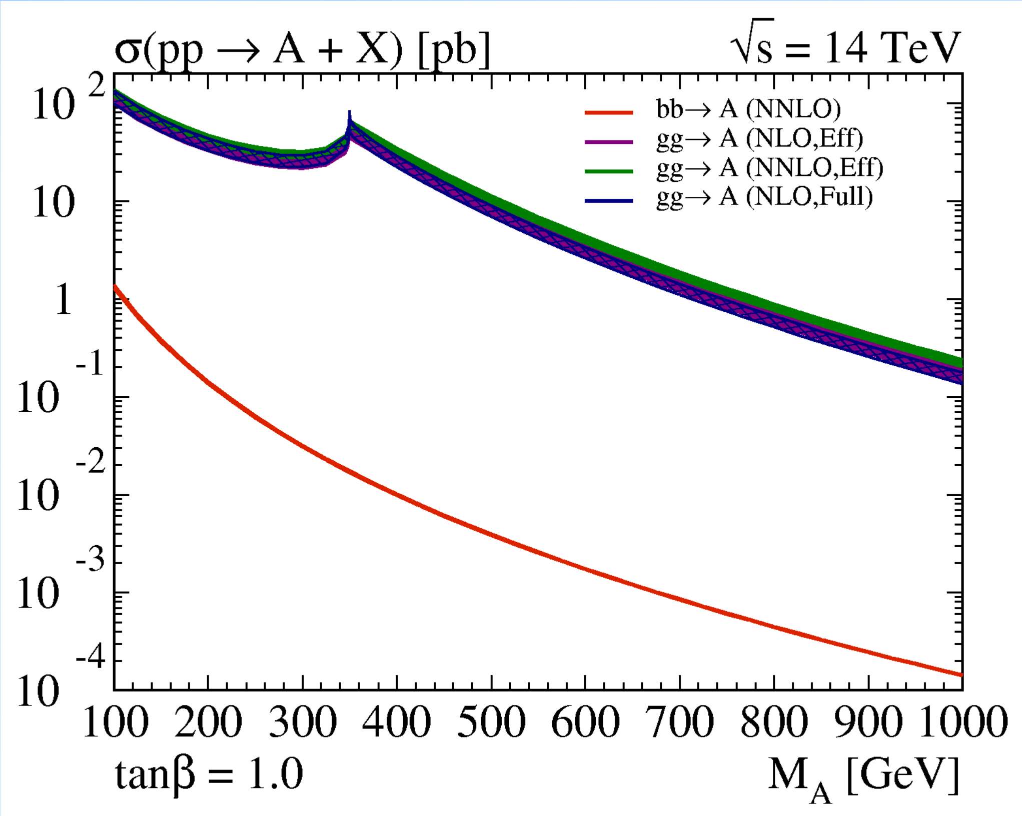
Comparison of 4FNS and 5FNS

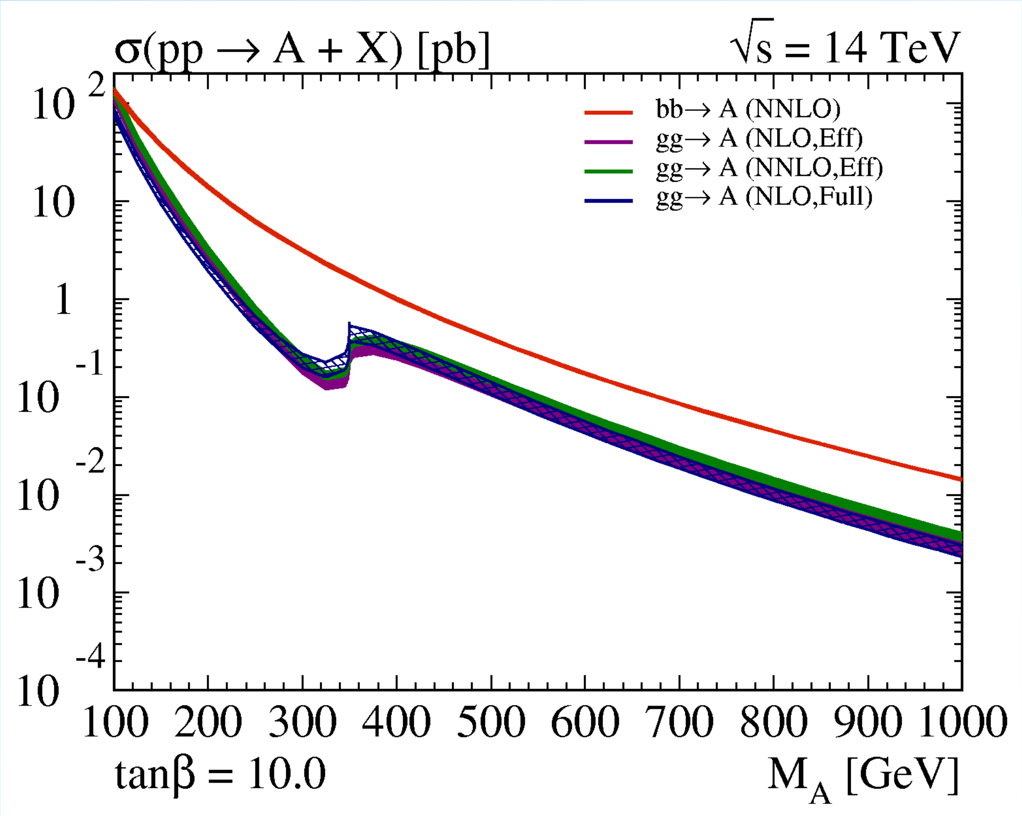


$b\bar{b} \to A$ versus $gg \to A$

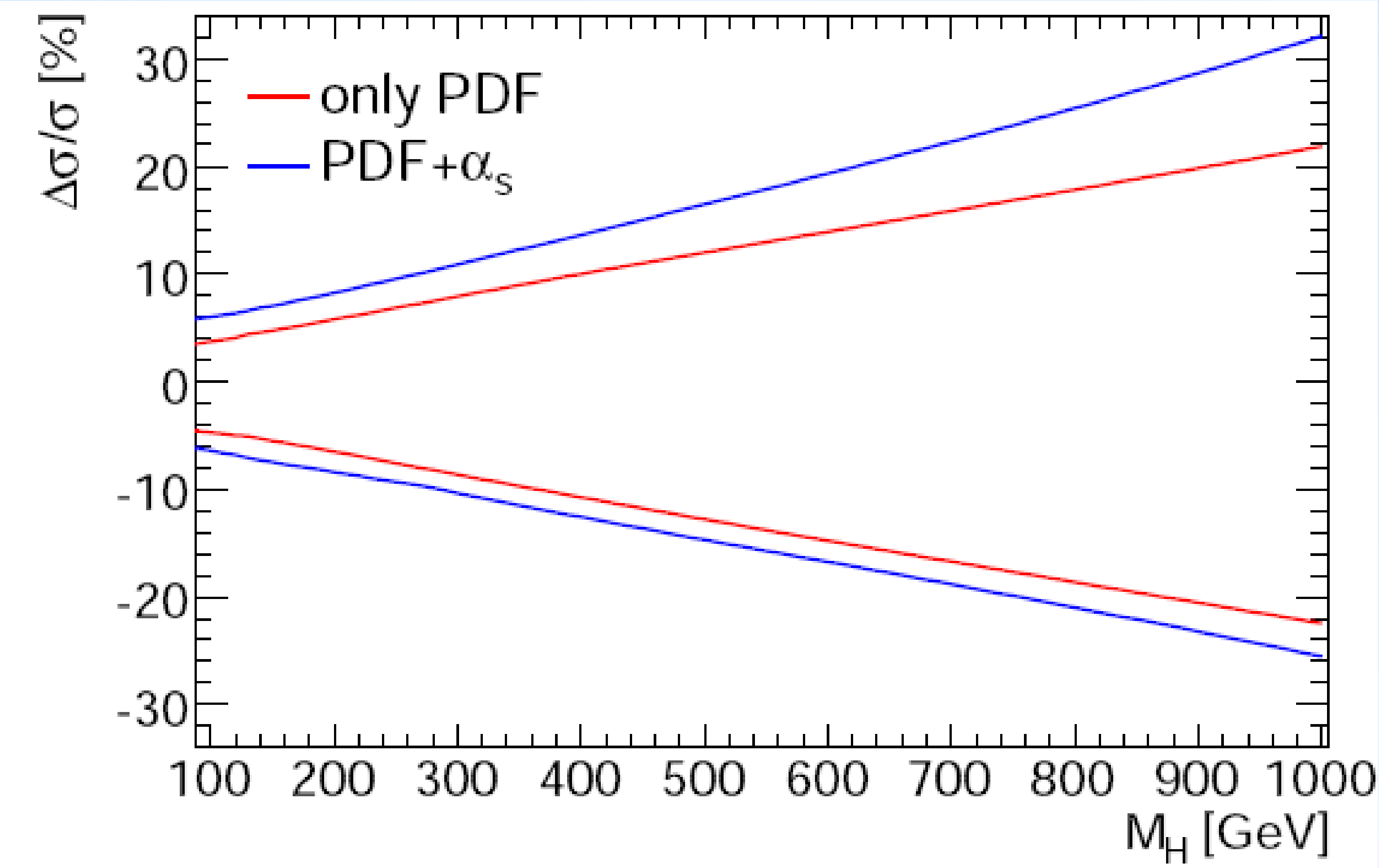
At small tan β, b quark fusion is tiny.

At large tan β, it dominates.





PDF uncertainty



bbH@NNLO, MSTW2008, sqrt(s)=7 TeV

So What's New in $b\bar{b} \to H/A$?

EW and SUSY Corrections!

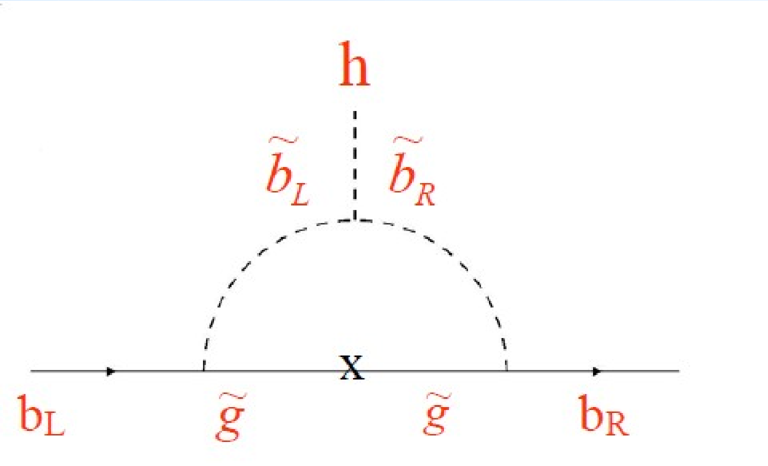
[Carena, et al. Hep-ph9912516],

[Dittmaier et al, hep-ph/0611353]

Radiative corrections involving massive electroweak and supersymmetric particles can be tan β enhanced. The dominant effect, however, is to renormalize the effective Hbb couplings, and to change the mixing between the CP even Higgs states.

Renormalized Effective Couplings

The tan β enhanced terms are "one-loop complete", which means that only the one-loop terms $\Delta_b \sim \alpha_{(s)}$ tan β. (Higher terms are ~ $\alpha^2_{(s)}$ tan β.) The one-loop terms can be summed



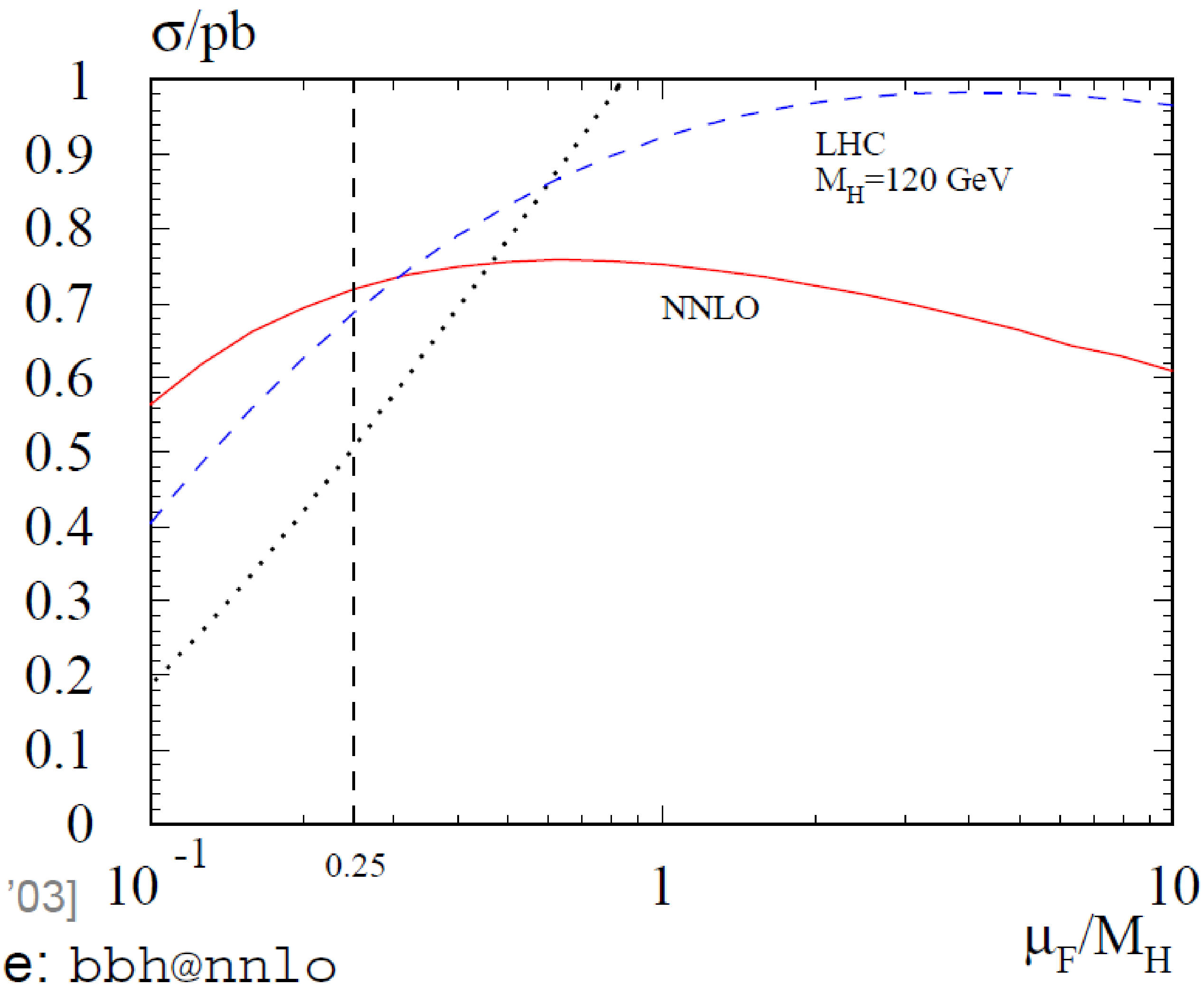
$$\frac{\lambda_b^h}{\lambda_b^{SM}} = -\frac{s_\alpha}{c_\beta}\frac{1-\Delta_b/(t_\beta t_\alpha)}{1+\Delta_b} \quad \frac{\lambda_b^H}{\lambda_b^{SM}} = \frac{c_\alpha}{c_\beta}\frac{1+\Delta_b t_\alpha/t_\beta}{1+\Delta_b} \quad \frac{\lambda_b^A}{\lambda_b^{SM}} = -t_\beta\frac{1-\Delta_b/t_\beta^2}{1+\Delta_b}$$

to give effective couplings that can be put into an Improved Born Approximation. Remaining SUSY/EW corrections are of order 1-3%. The corrections can be obtained from HDECAY or FeynHiggs.

Recommendations

The use of the μ_F~M_H/4 prescription has become ubiquitous and is seen as a way to account for the NNLO corrections. This is backwards! The NNLO corrections play a special role when using b partons and are essential for guaranteeing a consistent calculation. The μ_F~M_H/4 prescription is only justified when you don't have the NNLO corrections. The dominant effect of the SUSY/EW corrections is to renormalize the effective Yukawa couplings. The best prescription for inclusive production is to use the SUSY/EW effective couplings in the NNLO calculation.

Scale Dependence of $b\bar{b} \to H/A$ at LHC



[RH, Kilgore '03]

public code: `bbh@nnlo`

Summary

There has been great progress in understanding Higgs production from b quarks.

- The roles of VFNS and FFNS clarified.
- $b\bar{b} \to H$ dominates production for $\tan\beta \geq 7$!
- b parton distributions established as consistent.
- SUSY/EW Corrections are important for renormalizing effective couplings/mixings.
- The NNLO $b\bar{b} \to H$ calculation with SUSY/EW renormalized effective couplings should be used to compute inclusive signal cross sections.