Higgs Boson Production with b quarks

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Introduction

There has been a lot of work recently on Higgs Boson production with b quarks

- $gg \to b\bar{b}H$ @ NLO [Dawson, et al., Dittmaier, et al.]
- $b\bar{b} \to H/A$ @NLO [Maltoni et al.]
- $b\bar{b} \to H/A$ @NNLO [Harlander & Kilgore]
- $bg \to bH$ @NLO [Ellis, et al.]
- SUSY corrections to $bg \to bH$ @NLO

  [Hong-Sheng, et al., Cao et al.]

Why so much interest? … SUSY!

Standard Model Higgs

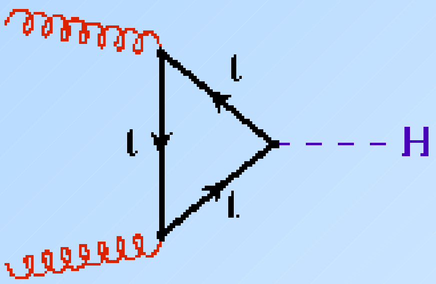
In the Standard Model, there is a single Higgs doublet which breaks electroweak symmetry, leaving one Higgs Boson and giving mass to the $W^{\pm}$ and Z bosons and to the quarks and leptons. The couplings are proportional to the masses

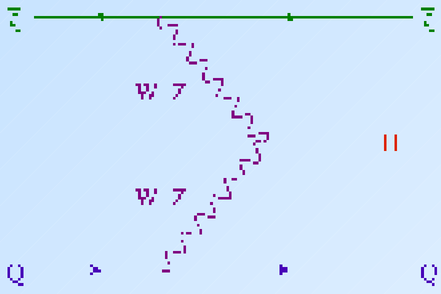
$$g_{WWH} = 2M_W/v \qquad g_{ZZH} = 2M_Z/v$$

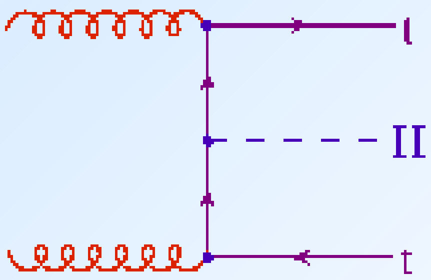
$$g_{ttH} = \sqrt{2}\, m_t/v \qquad g_{bbH} = \sqrt{2}\, m_b/v$$

Standard Model Higgs Boson Production

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

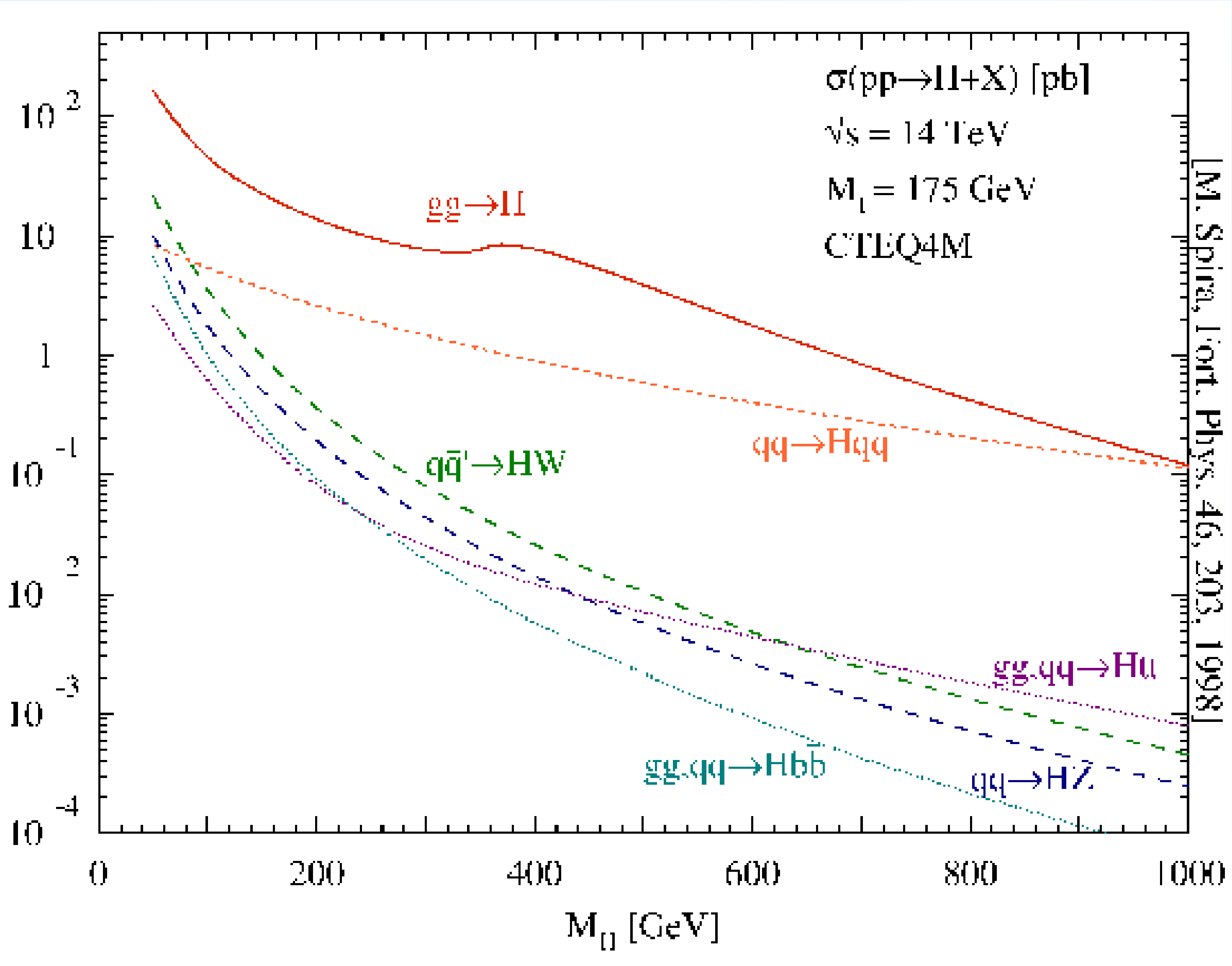






SM Higgs Production at the LHC

The most important channels are gluon fusion, WBF and $t\bar{t}H$.



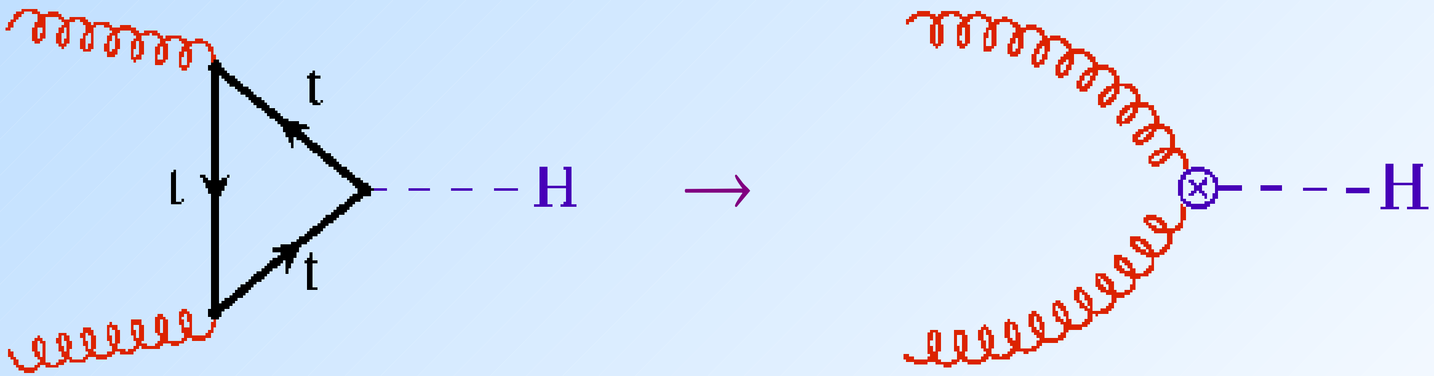
Effective Lagrangian

In the limit that the top quark is very heavy and all other quarks are massless, we can integrate out the top and formulate an effective Lagrangian coupling the Higgs to Gluons.

$$\mathscr{L} = C_1 \, H \, G^{\mu\nu} G_{\mu\nu}$$

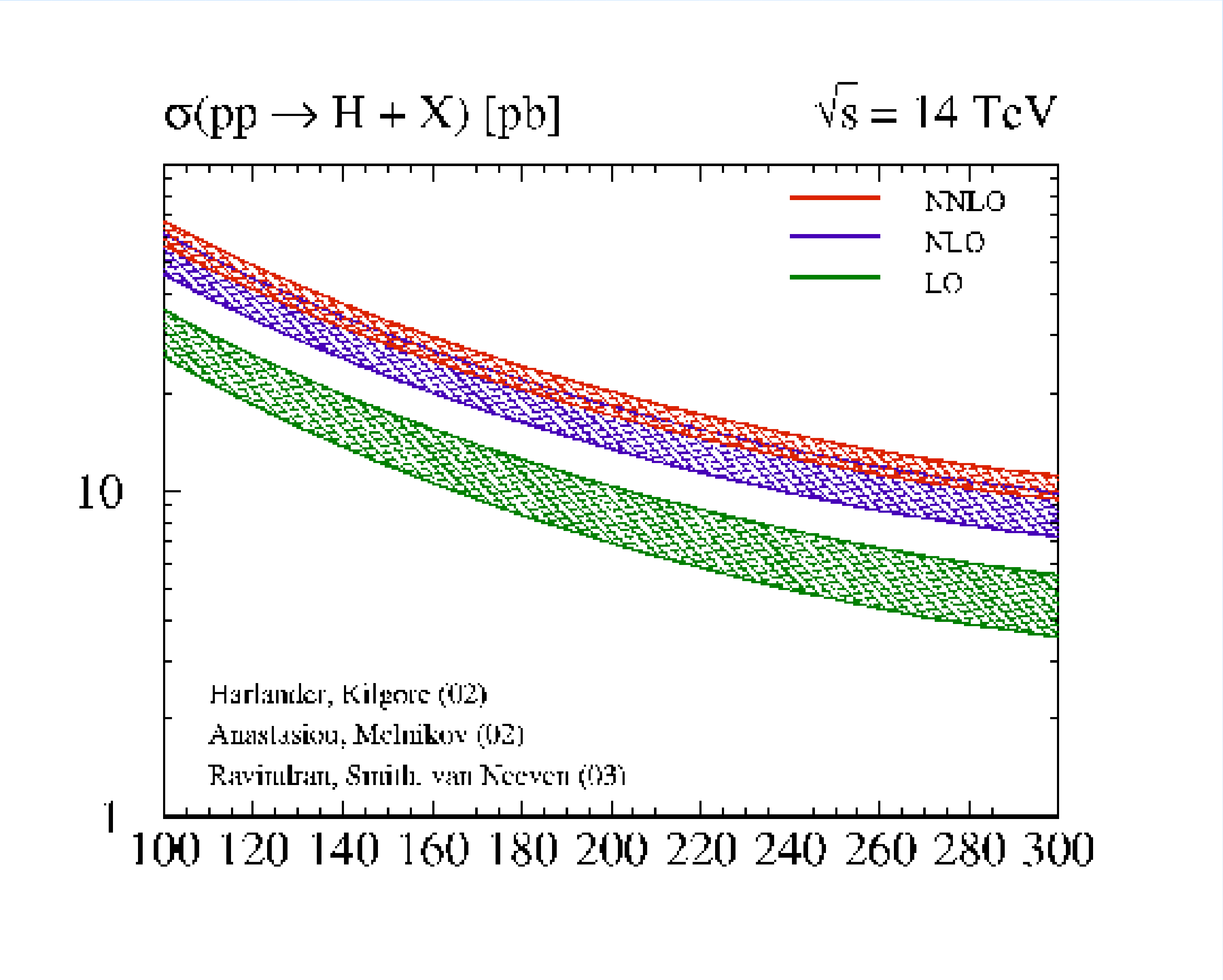
C_1 has been computed to order α_s^4 ! Chetyrkin, Kniehl, Steinhauser

Using the effective Lagrangian greatly simplifies the calculation of radiative corrections.



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, with vacuum expectation values v_u, v_d. After symmetry breaking, there are 5 physical Higgs Scalars:

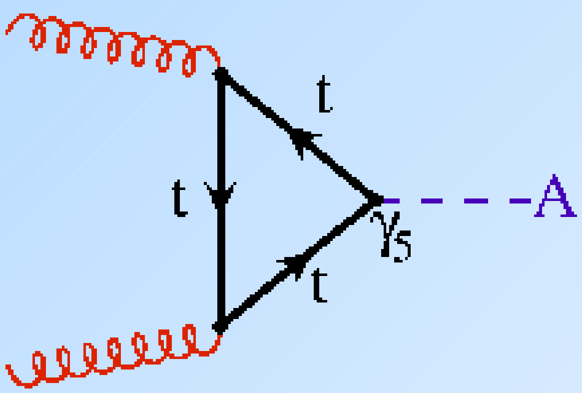
$$h^0,\ H^0,\ A^0,\ H^\pm$$

In the "decoupling" limit, the light neutral scalar, h^0, has properties almost identical to the Standard Model Higgs. The heavy scalar, H^0, and the pseudoscalar, A^0, have very different interactions.

Pseudoscalar Production

Gluon fusion is also very important to pseudoscalar production and can also be described by an effective Lagrangian in which the top quark is integrated out. This effective Lagrangian coupling the pseudoscalar to gluons is:

$$\mathscr{L} = C_1 A\, \varepsilon_{\alpha\beta\mu\nu} G^{a\,\alpha\beta}\, G^{a\,\mu\nu} + \ldots$$



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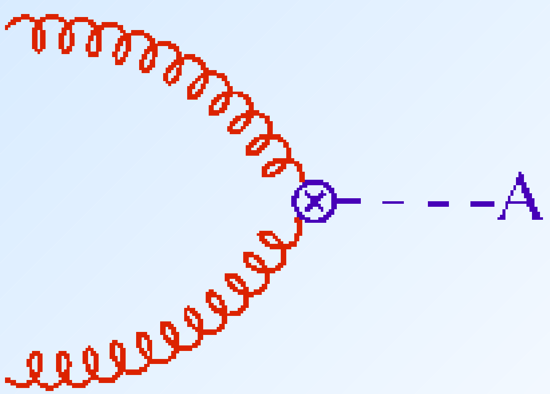


SUSY Higgs Production

SUSY Higgs production has also been computed using massive fermions to NLO.

Spira, Djouadi, Graudenz, Zerwas

NNLO Pseudoscalar production is computed in the same way as scalar production. But the effective Lagrangians are only valid for top quark loops!

Harlander, WK; Anastasiou, Melnikov; Ravindran, Smith, van Neerven

For scalar Higgs production in SUSY, you can also add squark/gluino effects.

Harlander, Steinhauser; Dawson, Djouadi, Spira

H/A Couplings

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

For $\tan\beta$ significantly larger than 1, b-quark interactions are important. But ... one cannot formulate an effective Lagrangian by integrating out the b-quark to produce ~100 GeV Higgs bosons! An NNLO calculation would require massive 3-loop diagrams.

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:

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

$gg \to b\bar{b}H$ ($\sigma_{b\bar{b}}$) can dominate at large tan β because

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

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

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 3) 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.

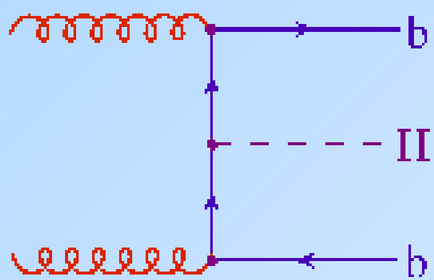
Parton Distributions in VFNS

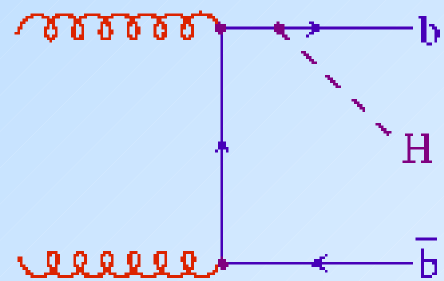
The CWZ scheme for the running of α_s can be extended to parton distributions. Below threshold, the parton distribution is taken to vanish. At the production threshold, gluons are allowed to start splitting into heavy quark pairs. Above threshold, evolution is governed by the RGE (Altarelli-Parisi).

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

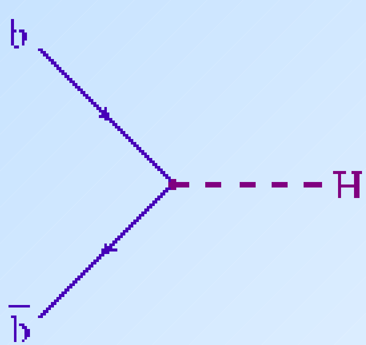
Parton Distributions in VFNS

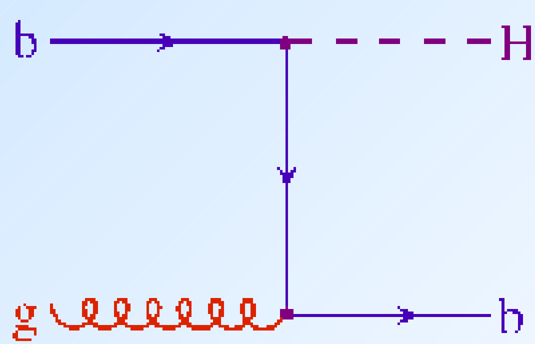
Logarithmic terms arise from forward emission of on-shell b-quarks





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





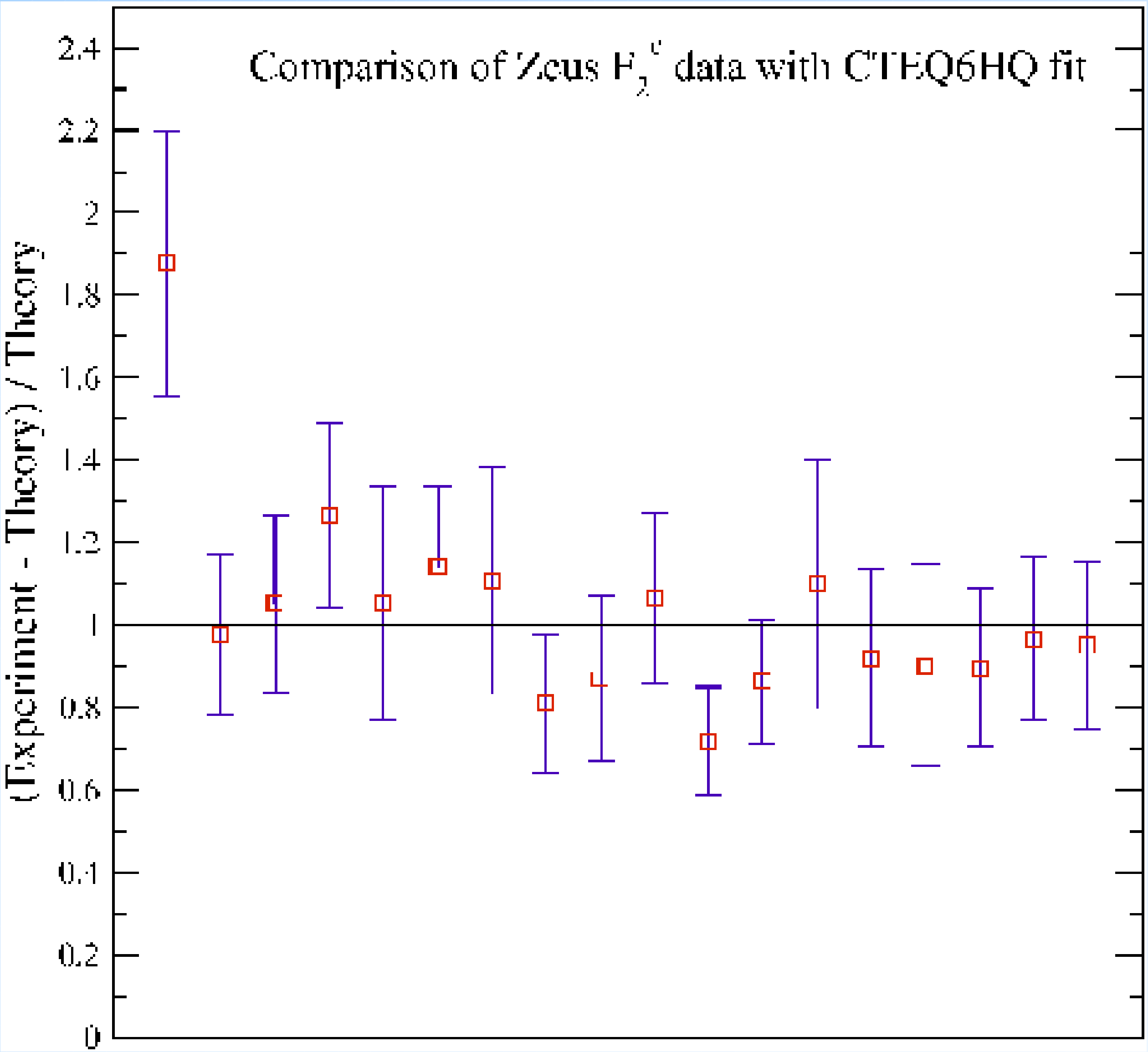
VFNS: Separating the Matching and Switching scales

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! One can use the full kinematics of heavy flavor production in the matching condition.

Both MRST and CTEQ have produced PDFs that take threshold information into account in the matching condition.

The heavy quark PDFs are still dominated by the gluon fit.

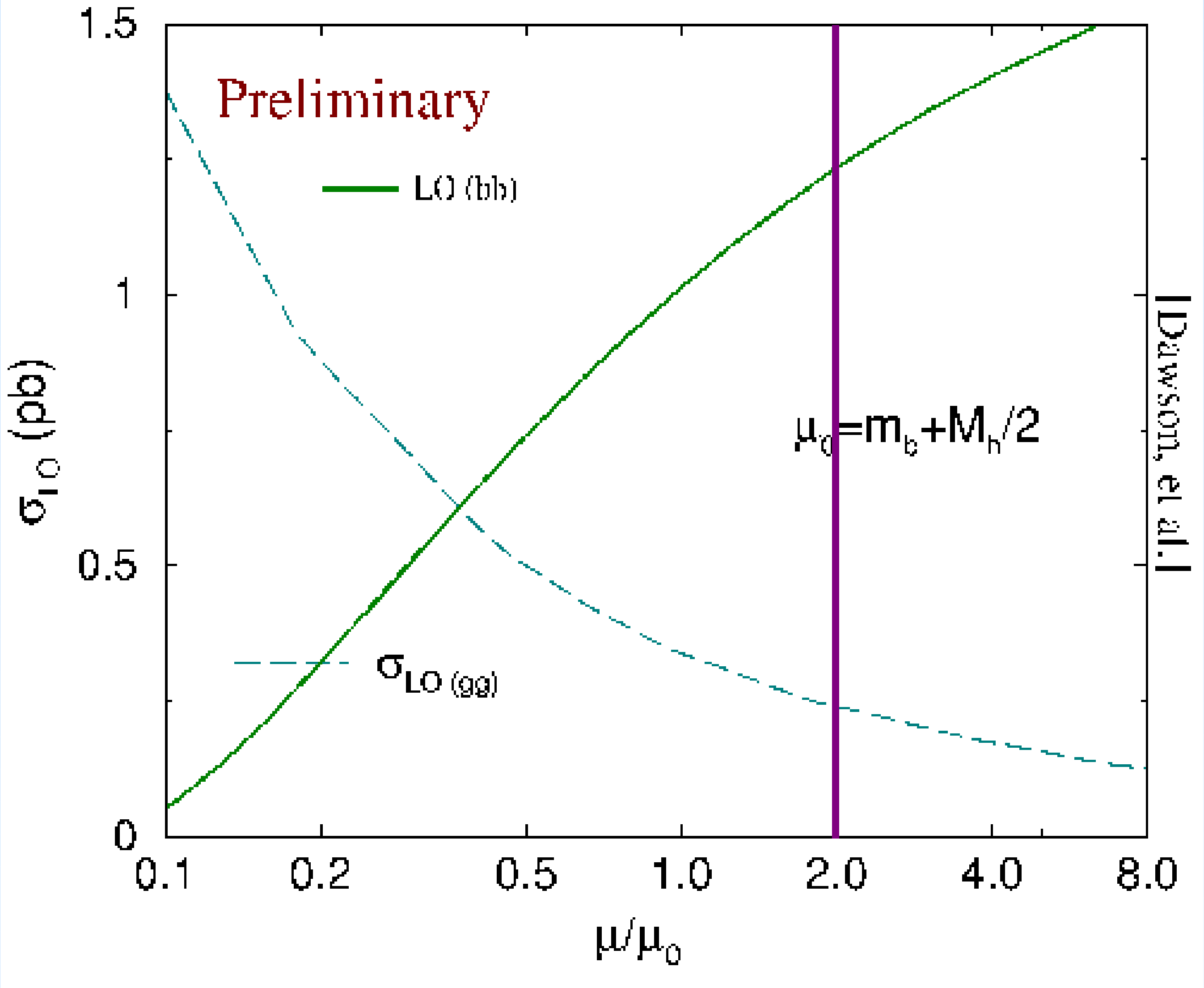
VFNS: Fits to F_2^c



(x and Q^2 bins combined)

Worries about the VFNS

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

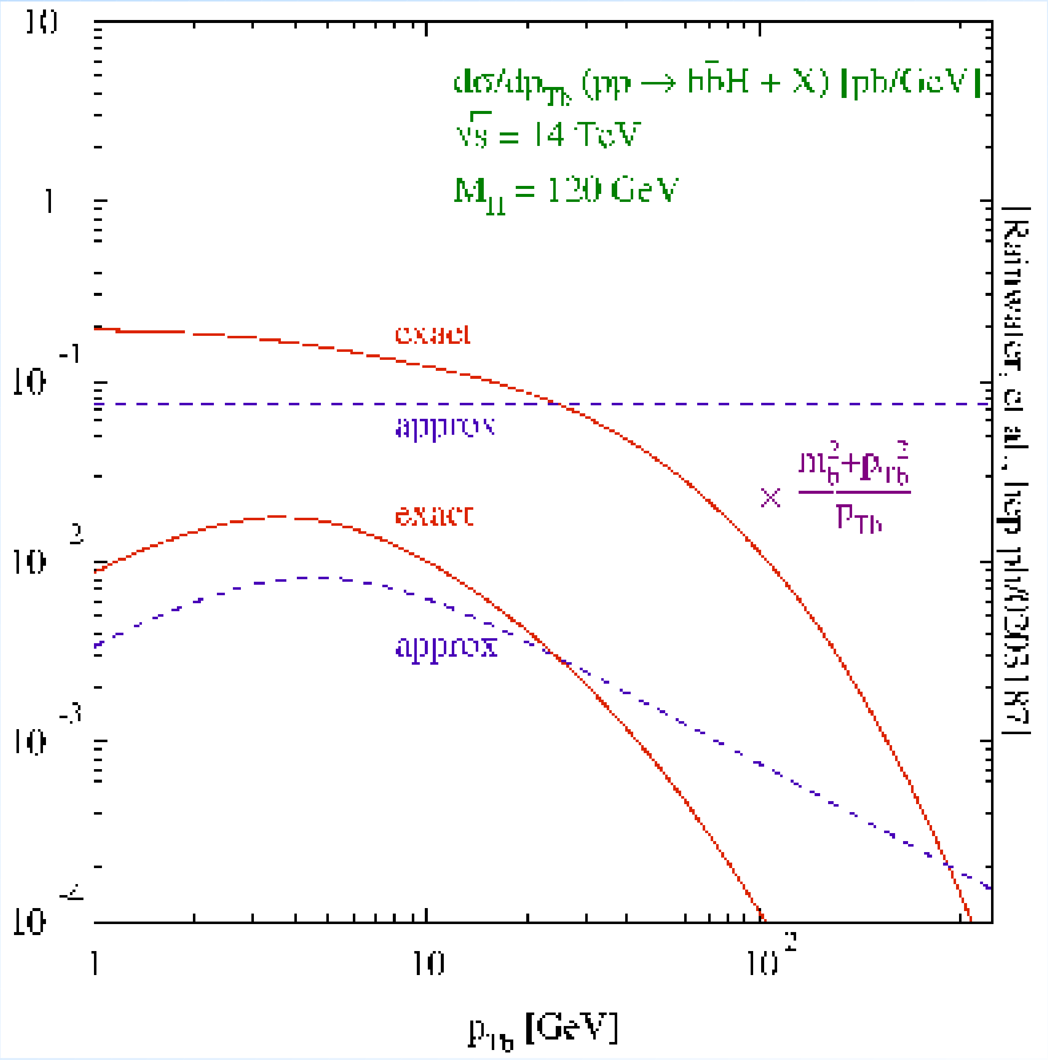


Factorization in the VFNS

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

[Rainwater, Spira, Zeppenfeld]

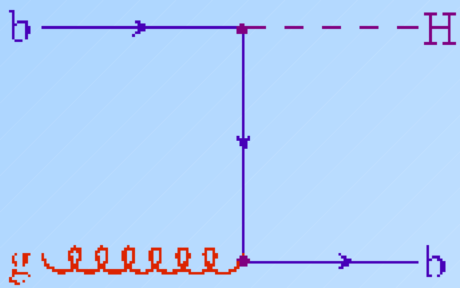
The "exact" curve is the full $\sigma(gg\rightarrow b\bar{b}H)$, while the "approximate" curve is the factorized collinear part. Proper factorization requires that the approximate term scale like $p_{Tb}/(m_b^2+p_{Tb}^2)$. Clearly the scaling falls at $\mu < M_H$.



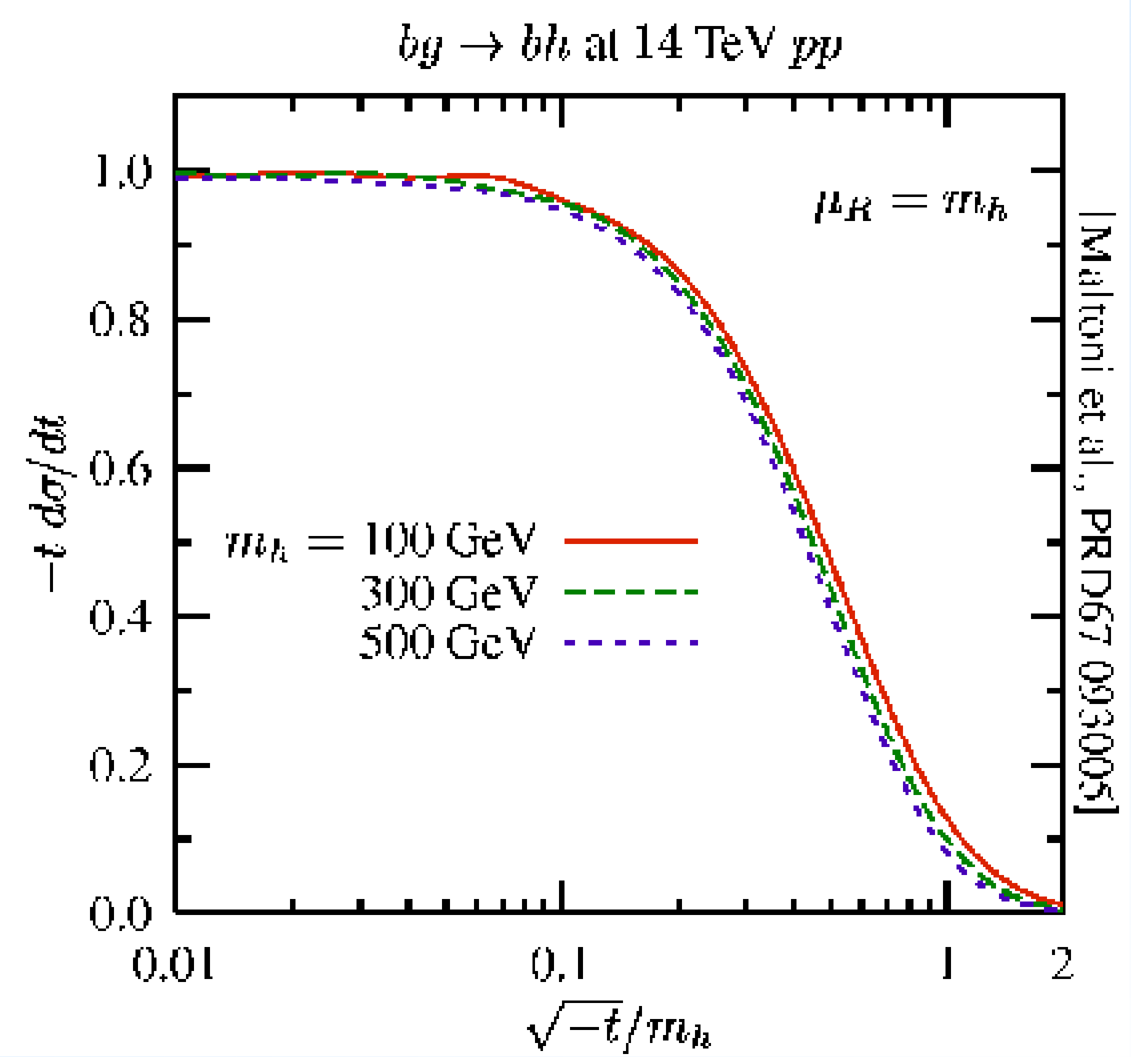
Factorization: A different spin

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 $\mu_F \sim \sqrt{-t^*}$.



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: ($\mu_F \sim M_H$)

$$\sigma_{bb} = \sum_{n=0}^{\infty} (\alpha_s \ln(M_H/m_b))^n \Big\{ \alpha_s^2 \left[c_{n0} \ln^2(M_H/m_b) + c_{n1} \ln(M_H/m_b) + c_{n2}\right] + \alpha_s^3 c_{n3} + \alpha_s^4 c_{n4} + \alpha_s^5 c_{n5} + \dots \Big\}$$

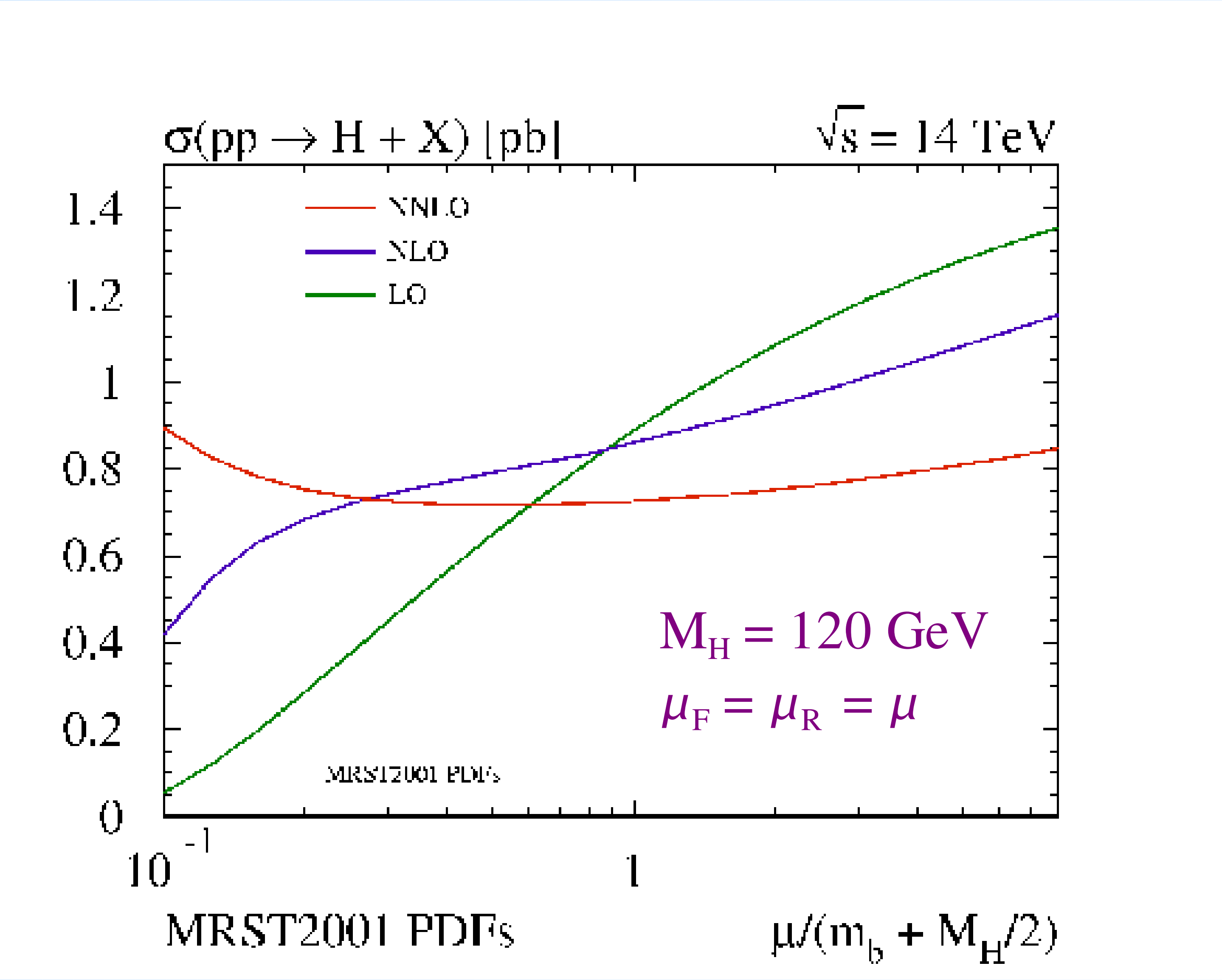
Inclusive Higgs production in VFNS

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 $bb \rightarrow H$ are identically equal to those for $bb \rightarrow A$.

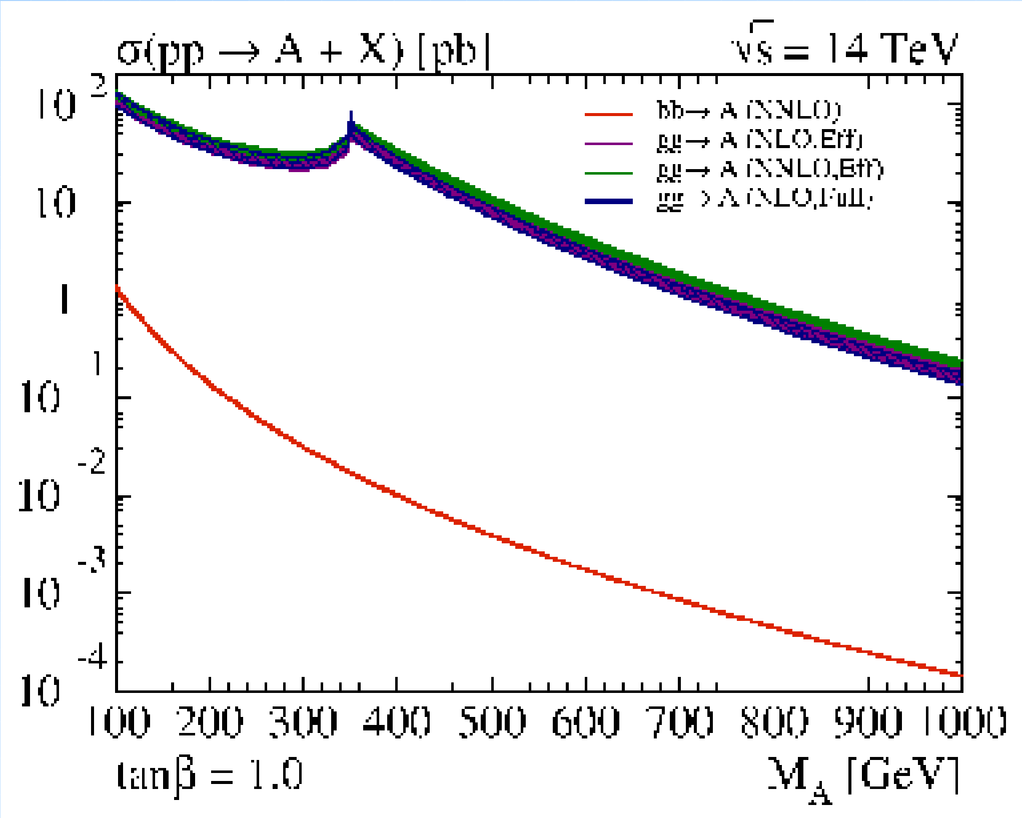
Scale Dependence of $b\bar{b}$ H/A at LHC

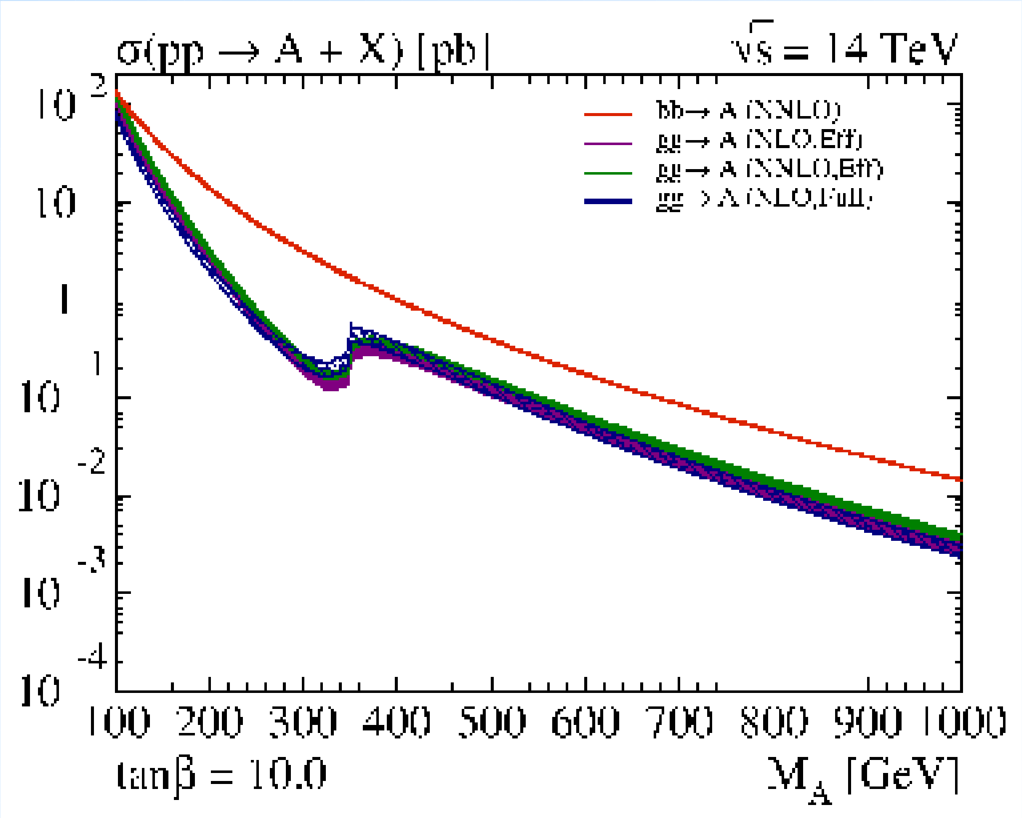


$b\bar{b} \to A$ versus $gg \to A$

At small tan β, b quark fusion is tiny.

At large tan β, it dominates.

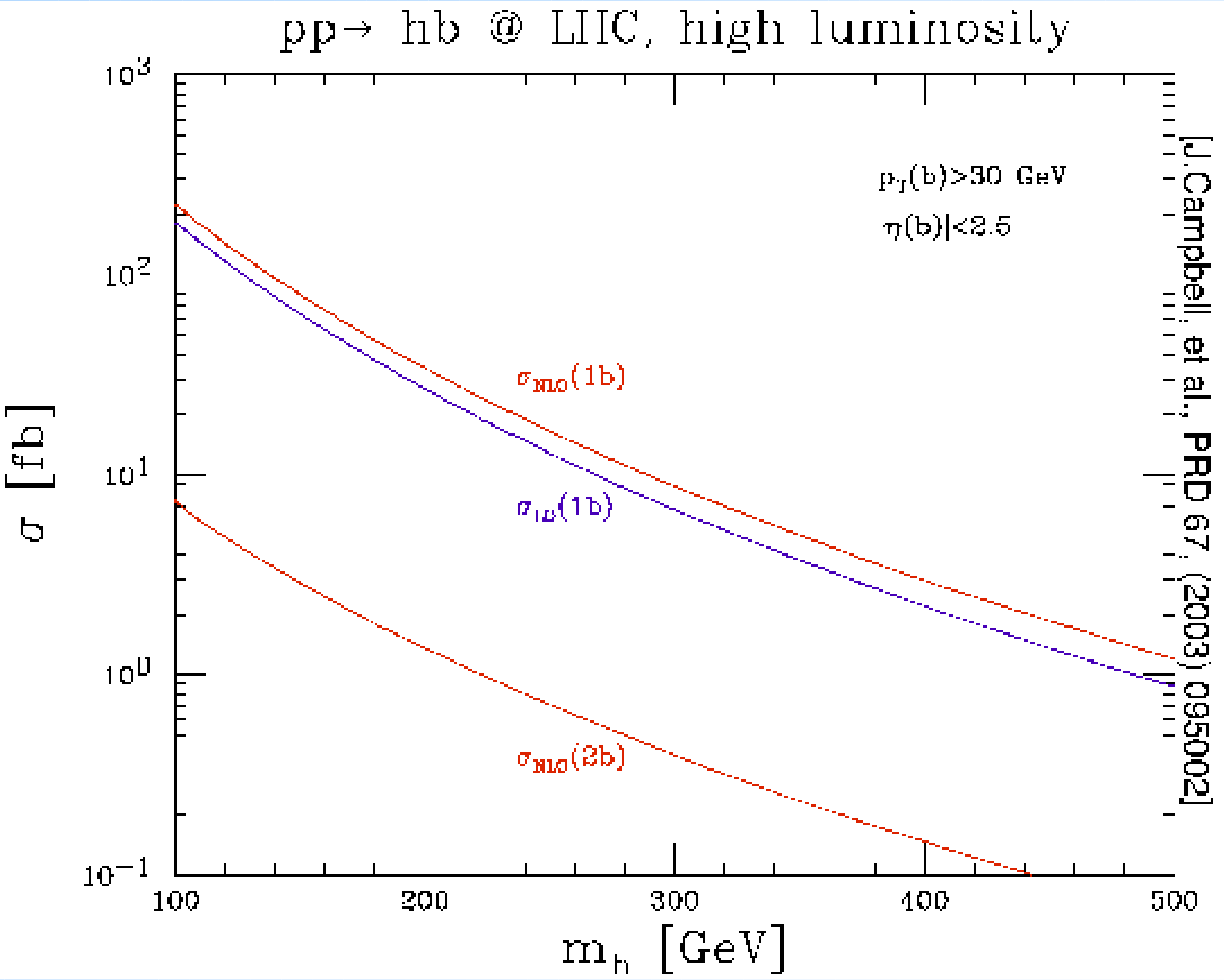




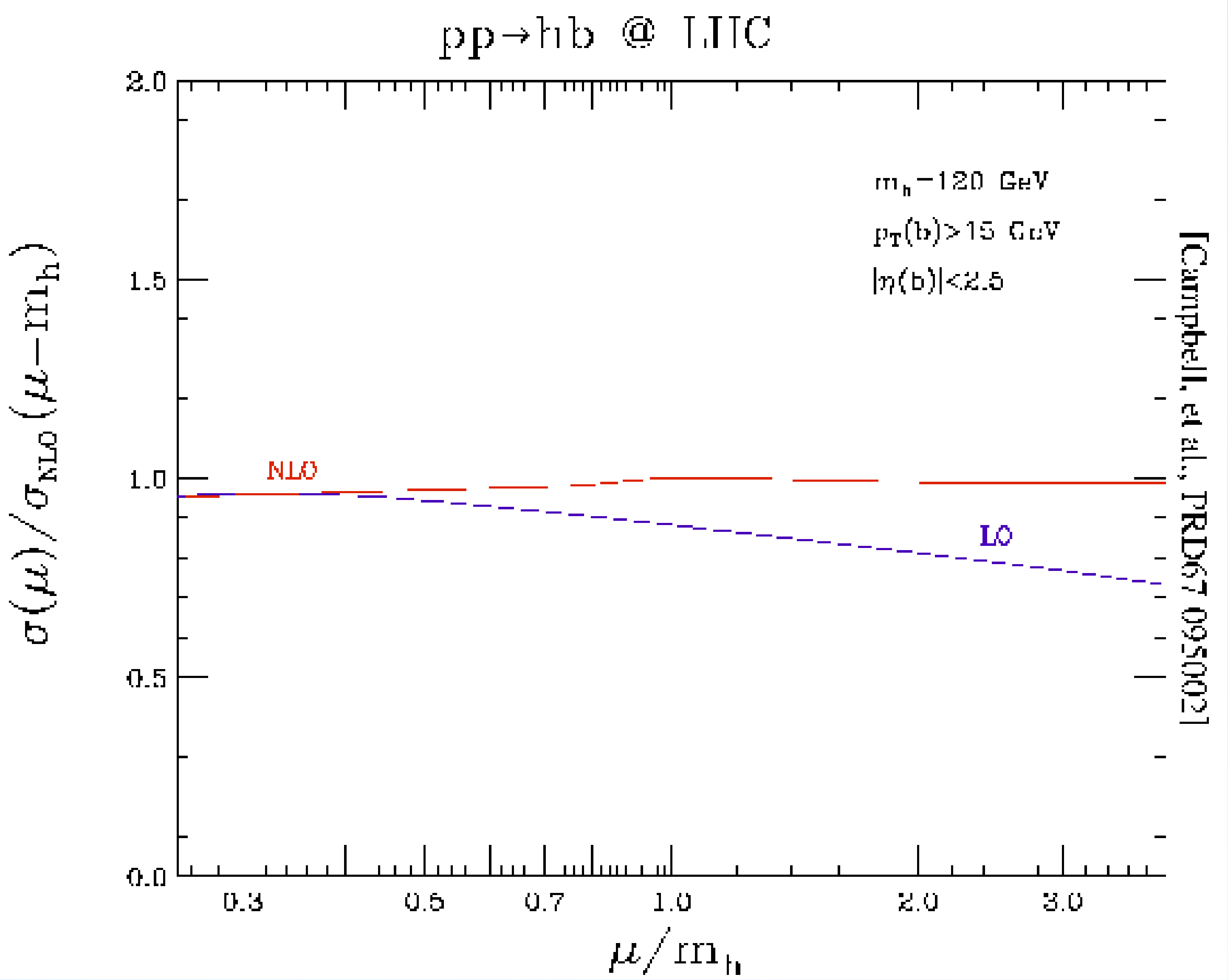
bg→bH @ NLO

Campbell, Ellis, Maltoni, Willenbrock

In bg→bH production, NLO is needed for a consistent result. When computed to the proper order, one gets a well-behaved calculation.

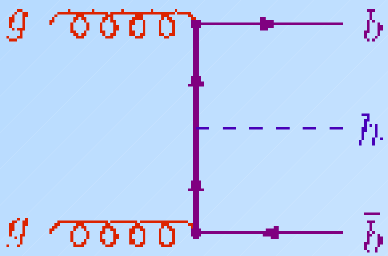


bg→bH Scale Dependence



Results for gg→b$\bar{b}$H @ NLO

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

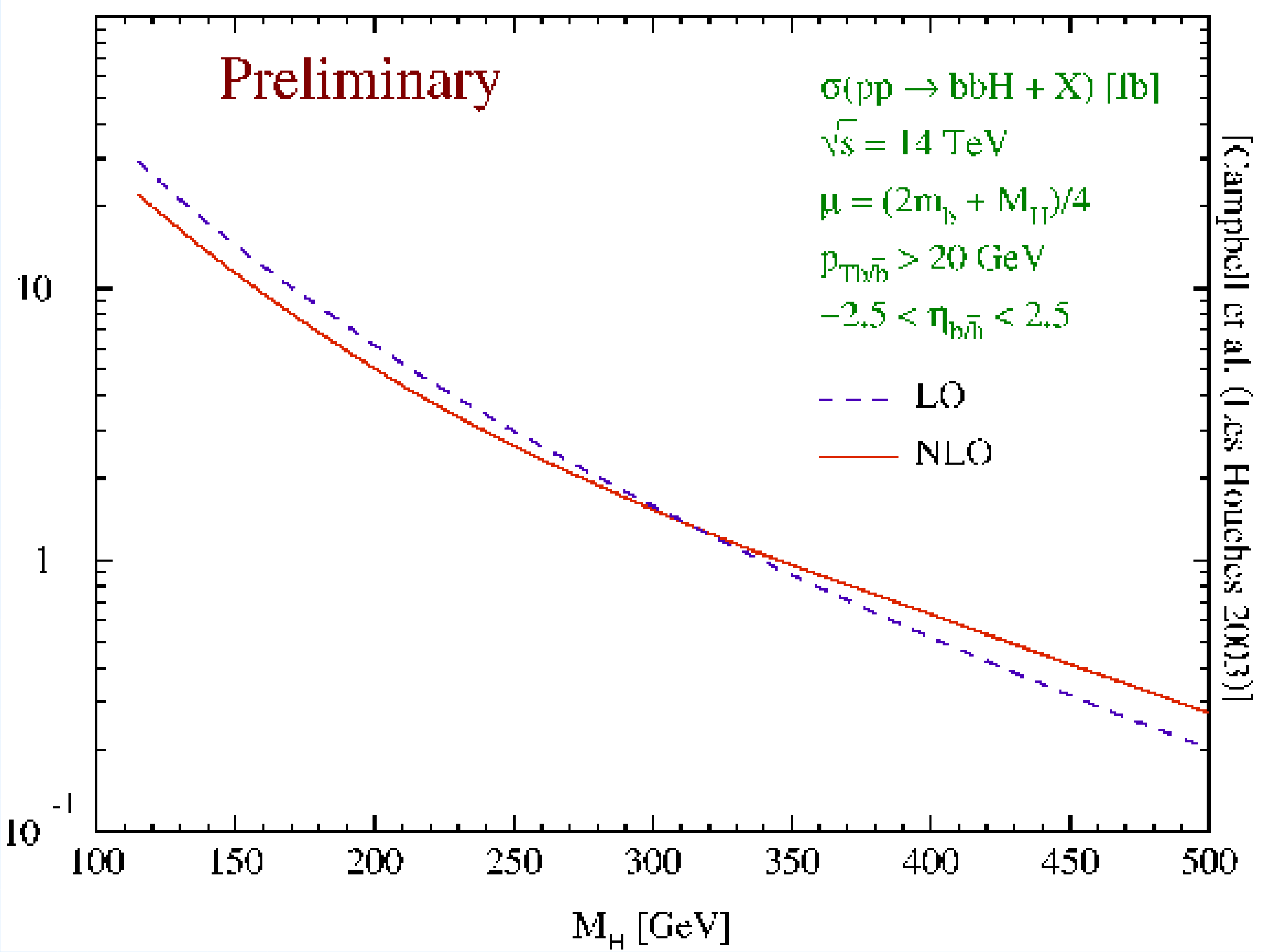


FFNS result for pp→b$\bar{b}$H @ NLO. This calculation goes to order α_s^3 (one order higher than the VFNS results) and includes more of the log-enhanced terms. This result is flexible in that it can be applied to the

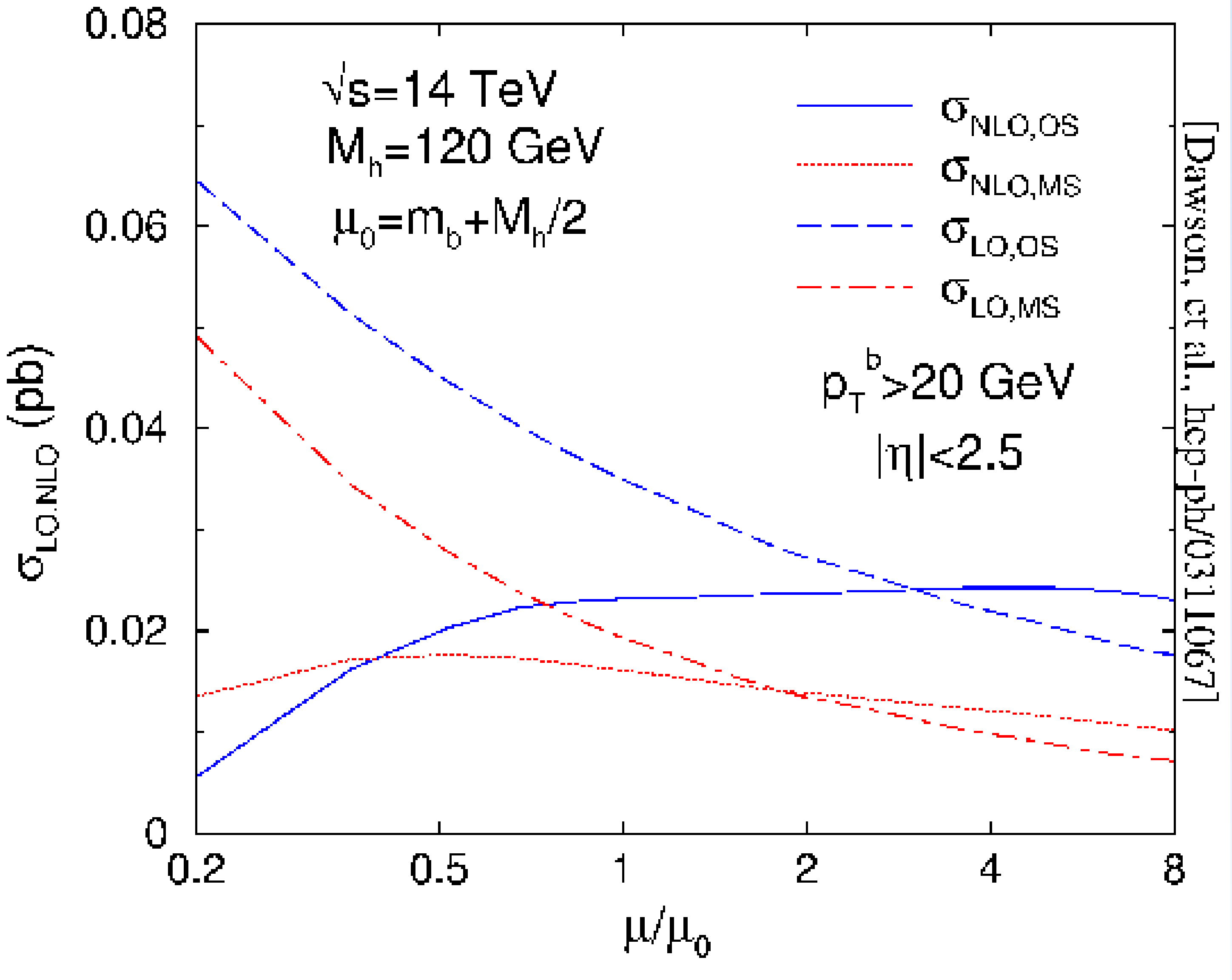
- Double tag mode
- Single tag mode
- Inclusive mode

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

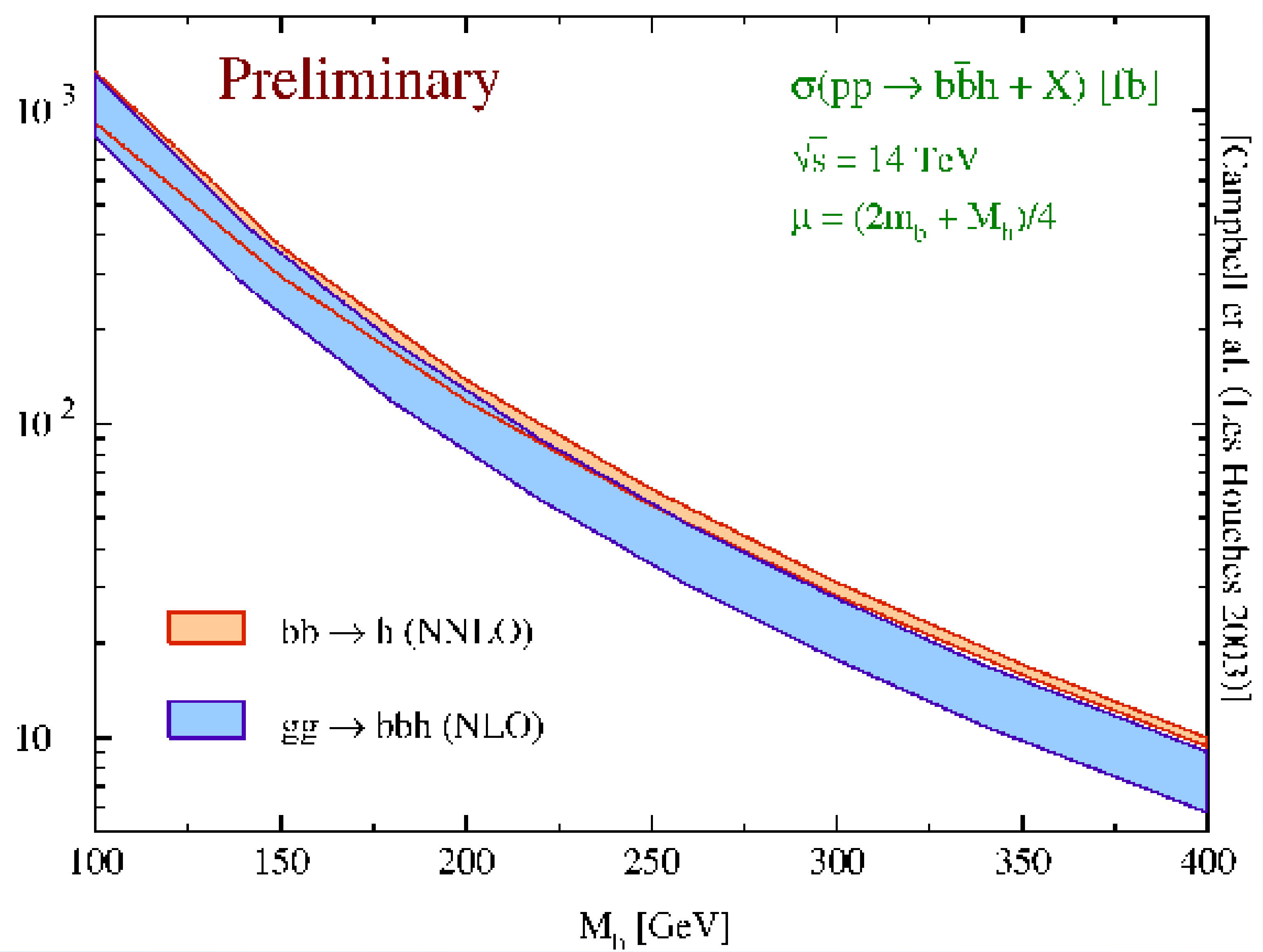
gg→$b\bar{b}H$ with two tagged b quarks



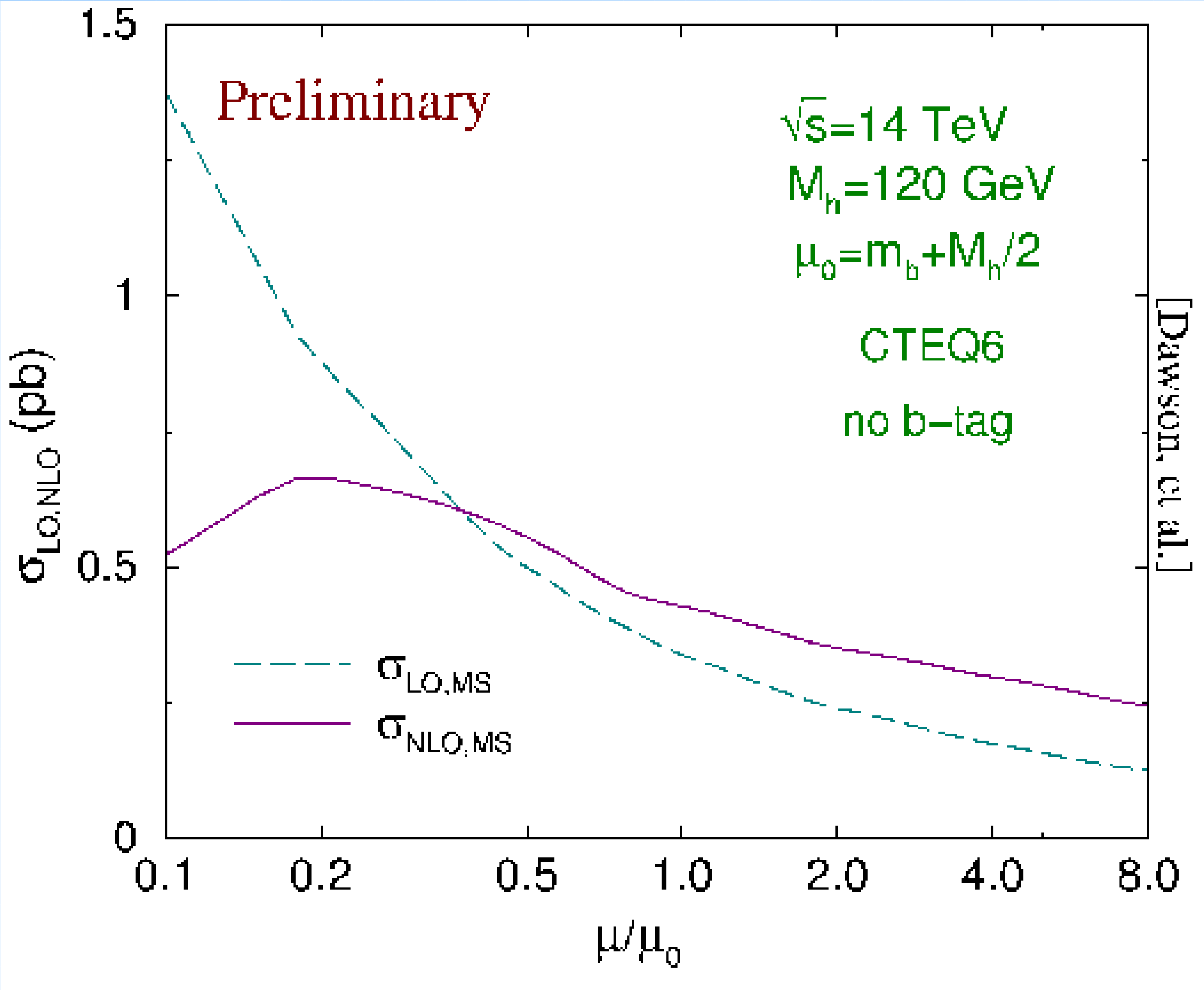
$gg \to b\bar{b}H$ with two tagged b quarks



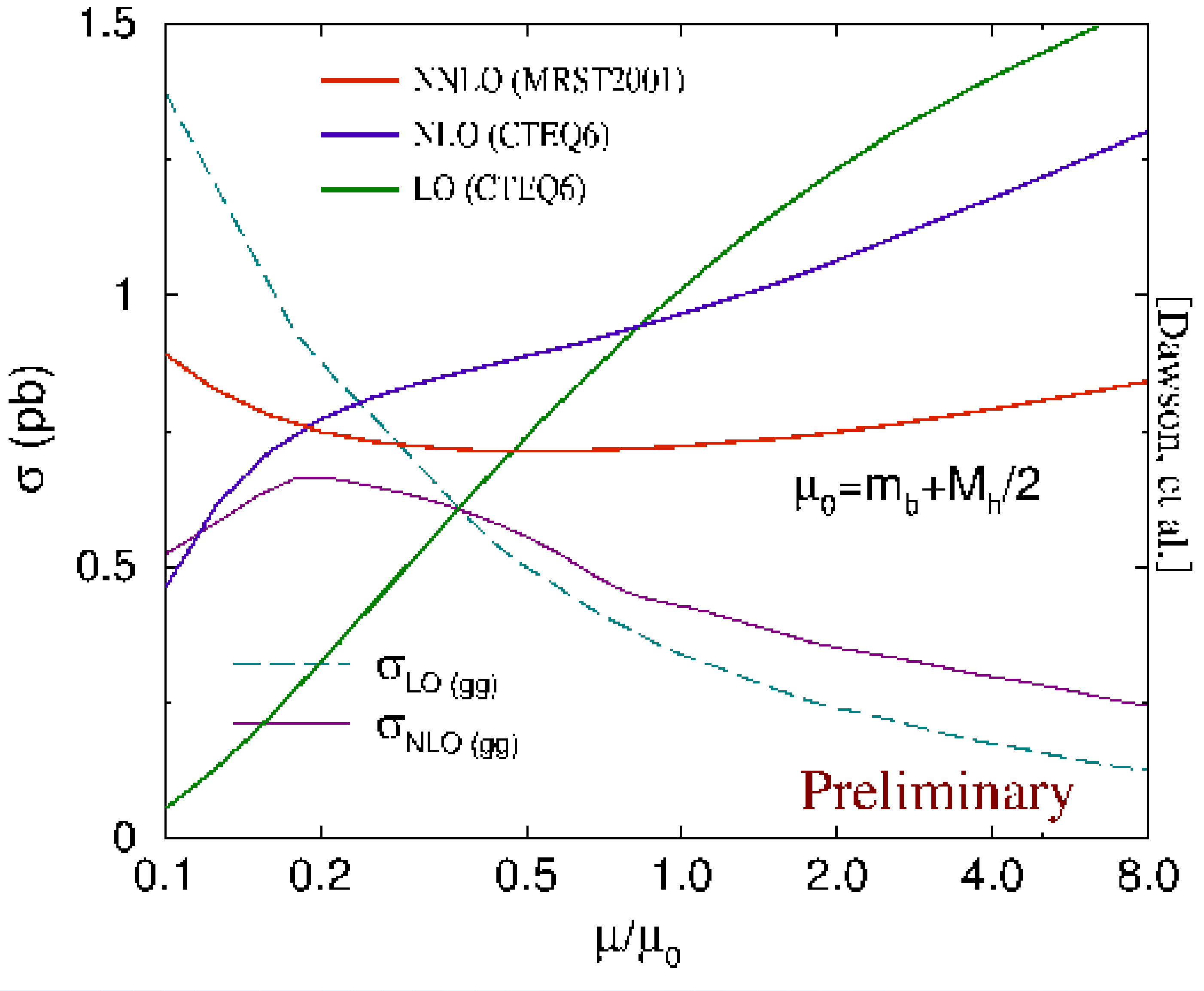
Preliminary results for inclusive $gg \to b\bar{b}H$



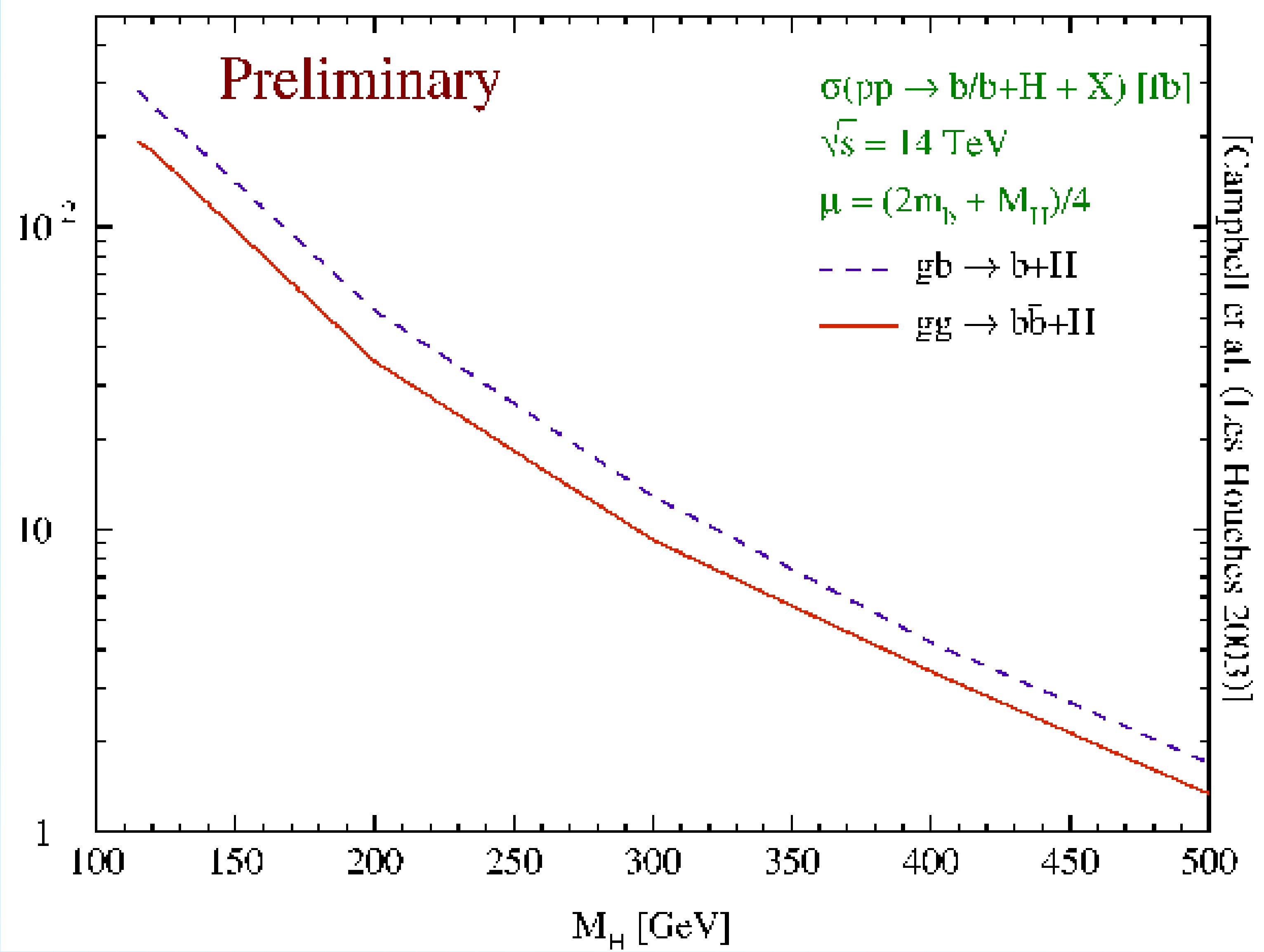
Preliminary results for inclusive $gg \to b\bar{b}H$



Compare $b\bar{b} \to H$(NNLO) to $gg \to b\bar{b}H$(NLO)



Compare bg→bH(NLO) to gg→b$\bar{b}$H(NLO)



Summary

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

- The dominant production mode for tan $\beta \geq 7$!
- The roles of VFNS and FFNS clarified.
  b parton distributions established as consistent.
  - $b\bar{b} \to H$ @ NNLO for inclusive mode
  - $bg \to Hb$ @ NLO for single tagged mode
  - $gg \to b\bar{b}H$ @ NLO for the double tagged mode
  - Consistency between $gg \to b\bar{b}H$ @ NLO with b parton results at the proper order.
- SUSY Corrections known @ NLO