

**Higgs Boson Production with Bottom Quarks
at Hadron Colliders**

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in collaboration with

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and

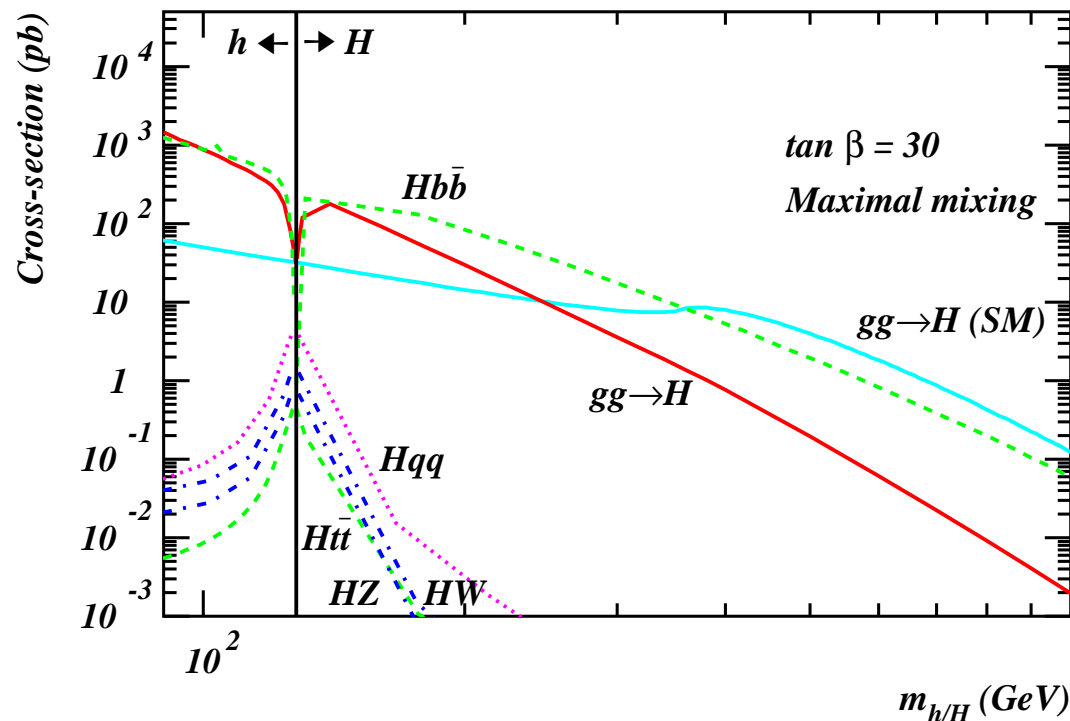
Laura Reina (FSU)

In the Standard Model (SM), Higgs boson production in association with b quarks is suppressed by the small b Yukawa coupling, $g_{bbh} = \frac{m_b}{v} \approx 0.02$.

In the MSSM, however, the cross sections to $p\bar{p}, pp \rightarrow b\bar{b}h, h = h^0, H^0, A^0$, are enhanced with respect to the SM for large values of $\tan\beta$:

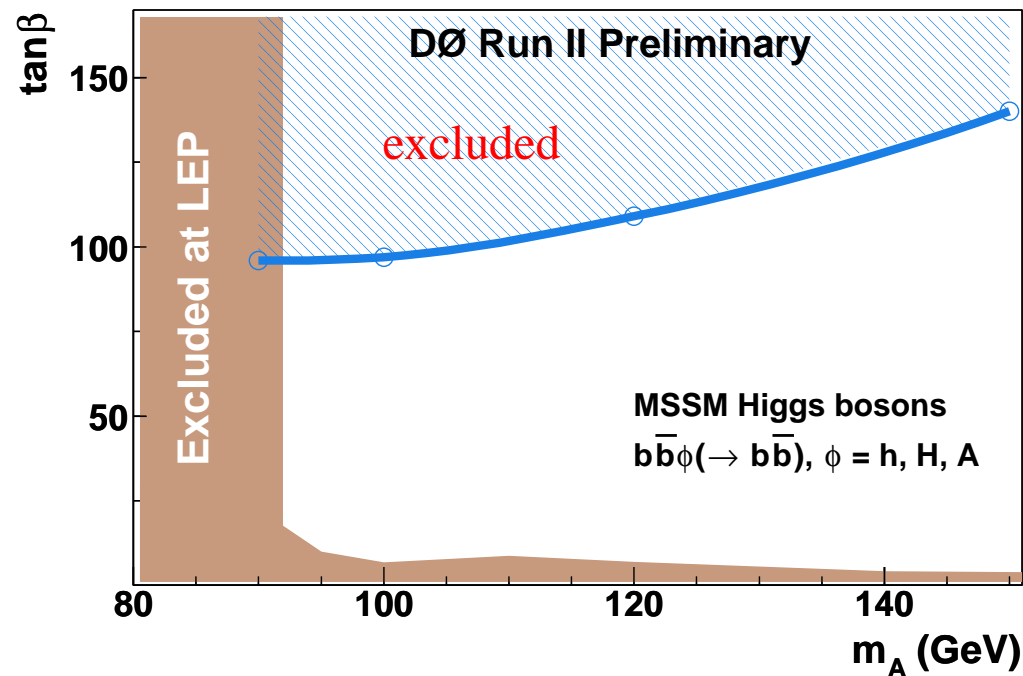
$$g_{bb(h^0, H^0)}^{MSSM} = \frac{(-\sin\alpha, \cos\alpha)}{\cos\beta} g_{bbh} \quad \text{and} \quad g_{bbA^0}^{MSSM} = \tan\beta g_{bbh}$$

For example, $\sigma(gg \rightarrow b\bar{b}H^0) > \sigma(gg \rightarrow H^0)$ for $\tan\beta > 30$ at the LHC ($\sqrt{s} = 14$ TeV):



from M.Carena, H.Haber,
 Prog.Part.Nucl.Phys.50 (2003)
 M.Spira, Fortschr.Phys.46 (1998)
 and hep-ph/9810289 (update)

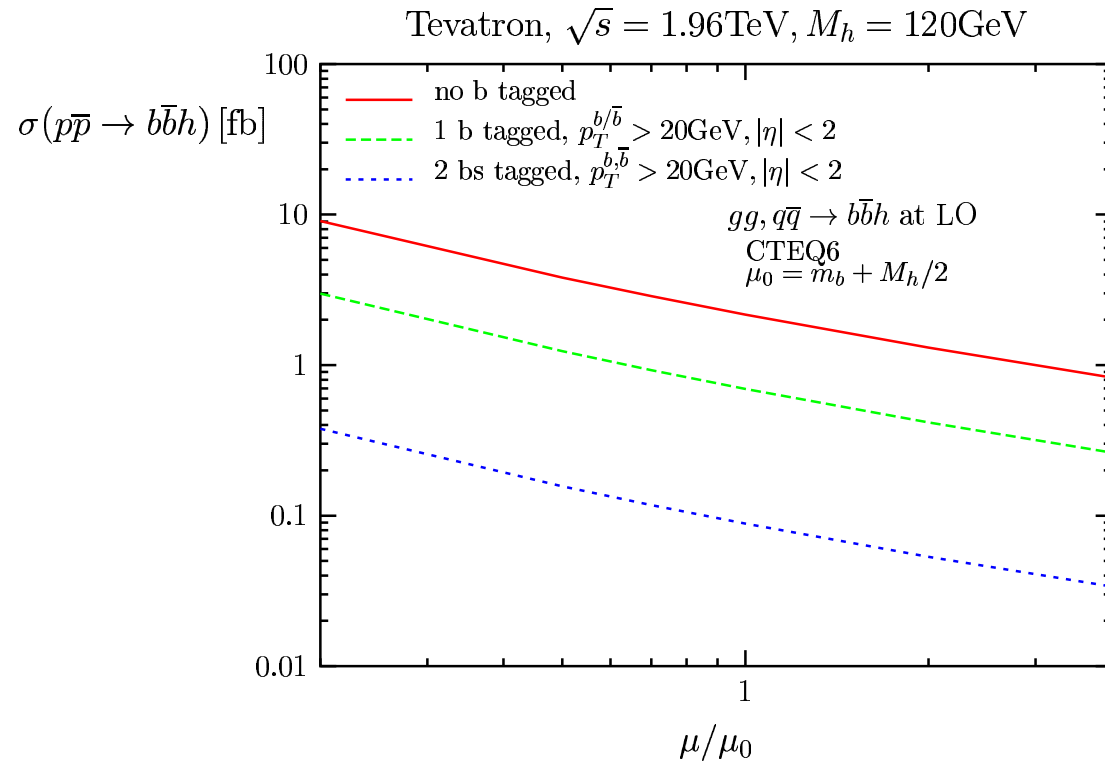
Search for MSSM H^0, h^0, A^0 in 3 b -tagged events using D0 Run II data:



from The D0 collaboration, D0 Note 4366 - CONF
see also talk by S.M.Wang, Moriond 2004
see also talk by A.Melnitchouk, Pheno 2004

Need for NLO QCD calculations

- LO calculations have very **strong renormalization/factorization scale dependence**:



- $\mathcal{O}(\alpha_s)$ corrections can strongly **increase/decrease** the total production rate.
- $\mathcal{O}(\alpha_s)$ corrections may **affect the shape of distributions**.

Exclusive $b\bar{b}$ Higgs production at hadron colliders

Status:

Two independent calculations based on $gg, q\bar{q} \rightarrow b\bar{b}h$ at NLO QCD by S.Dittmaier, M.Krämer, M.Spira (hep-ph/0309204) and S.Dawson, C.Jackson, L.Reina, D.W. (hep-ph/0311067). **They are in good agreement.**

We require two high p_T b quark jets in the final state:

$$p_T^{b,\bar{b}} > 20 \text{ GeV} \quad \text{and} \quad |\eta_{b,\bar{b}}| < 2(2.5) \quad \text{Tevatron (LHC)}$$

We consider the radiated gluon and the b/\bar{b} quarks as distinct particles only if

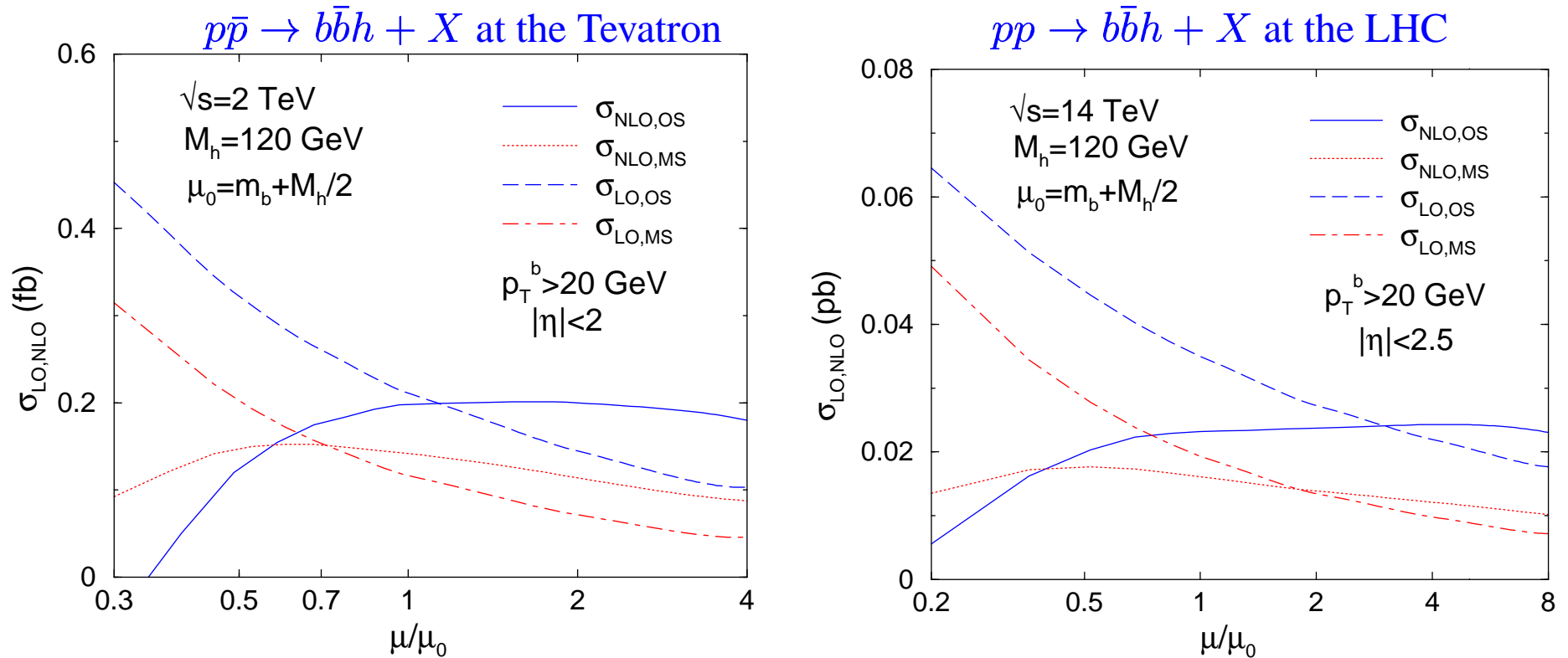
$$\Delta R = \sqrt{(\Phi_b - \Phi_g)^2 + (\eta_b - \eta_g)^2} > 0.4$$

Otherwise their 4-momentum vectors are combined into an effective b/\bar{b} momentum vector.

- These cuts reduce the signal, but also greatly reduce the background.
- Unambiguously proportional to the b quark Yukawa coupling.

Main Result

Drastically reduced scale dependence of the NLO QCD cross sections:

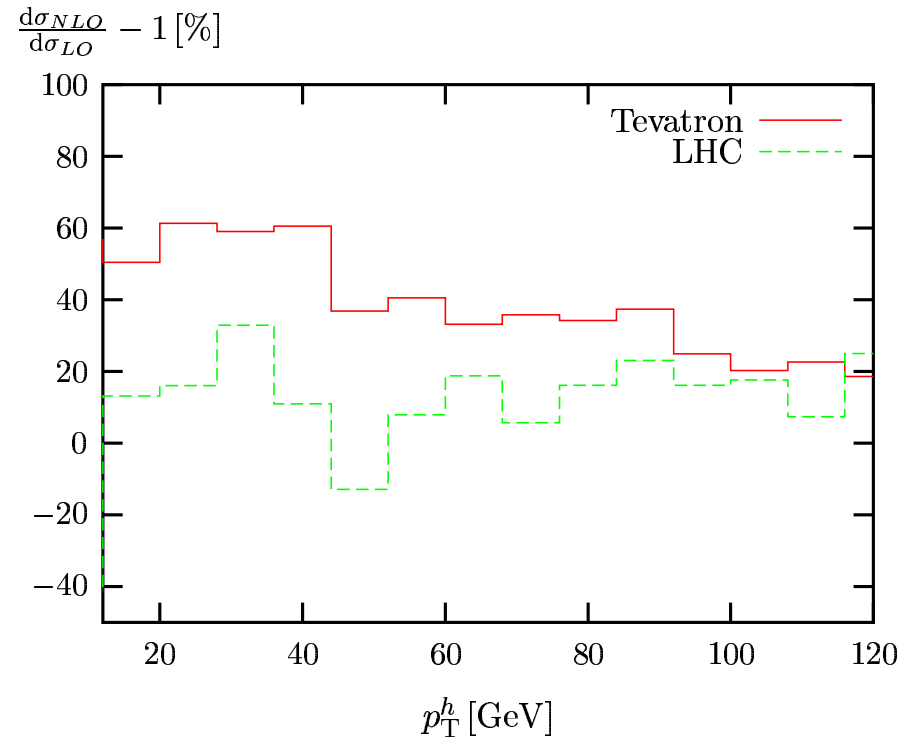
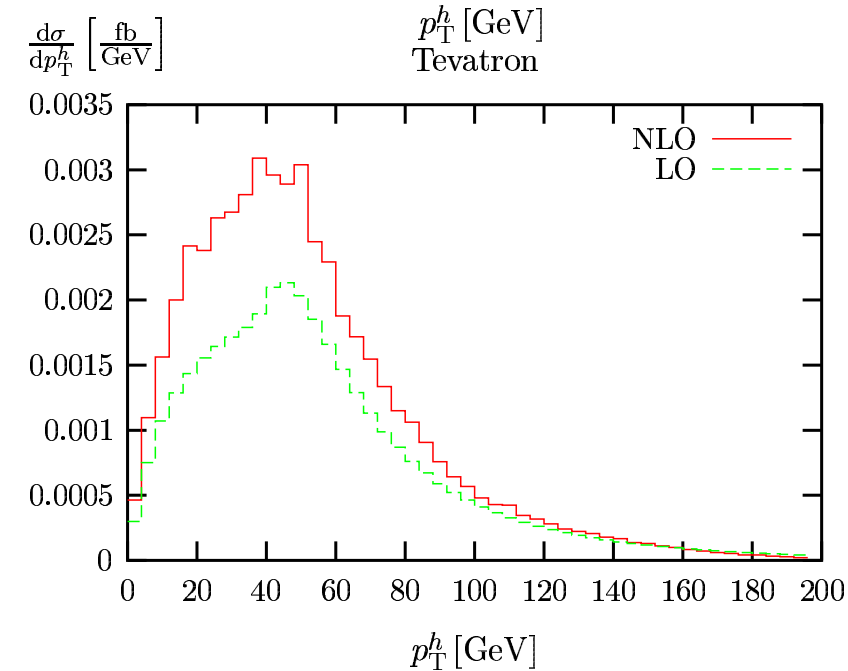
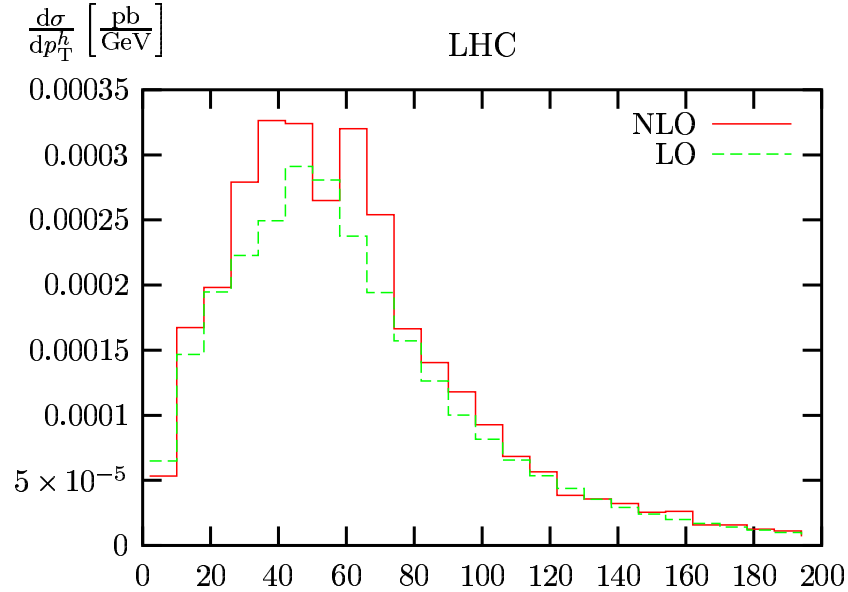


from S.Dawson, C.Jackson, L.Reina, D.W., hep-ph/0311067

see also S.Dittmaier *et al.*, hep-ph/0309204 and J.Campbell *et al.* in LesHouches 2003 proceedings

The b quark mass used in g_{bbh} is renormalized either in the on-shell (*OS*) or \overline{MS} scheme.

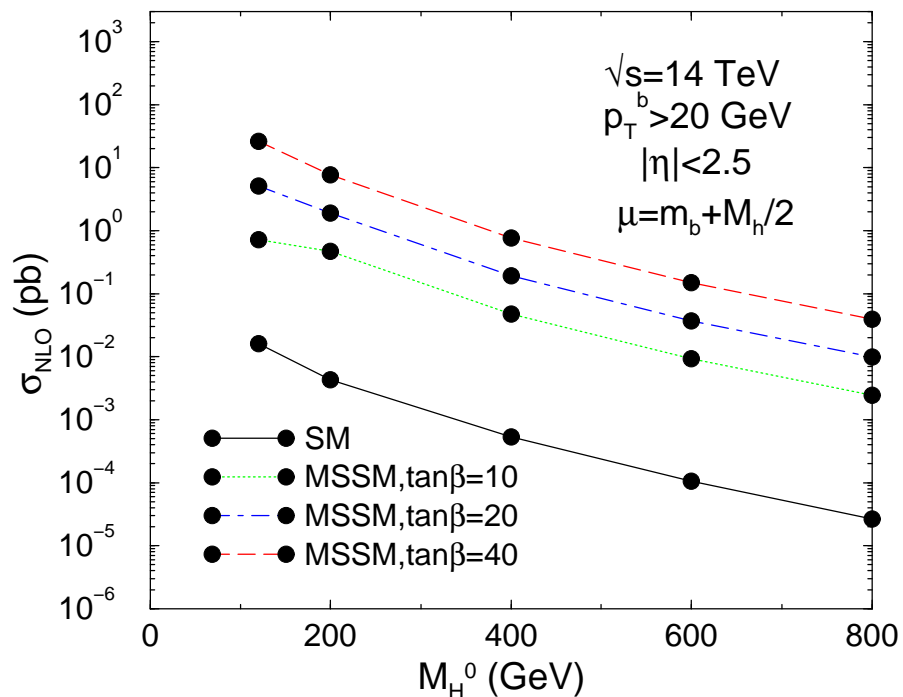
Effect of NLO QCD corrections on the Higgs p_T distribution:



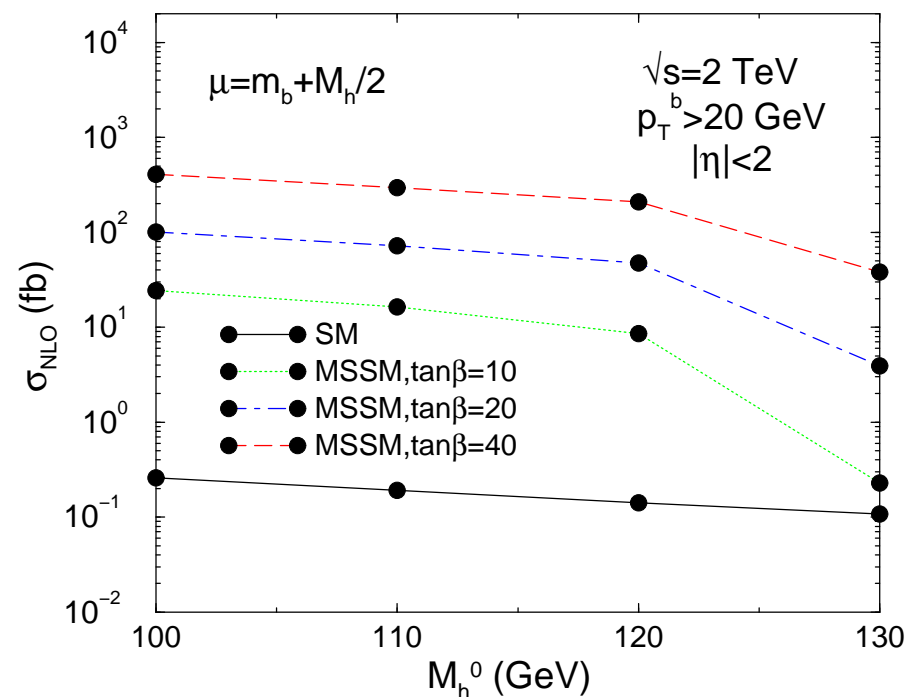
from S.Dawson, C.Jackson, L.Reina, D.W., hep-ph/0311067

$M_{(h^0, H^0)}, \tan \beta$ dependence in the MSSM

$pp \rightarrow b\bar{b}H^0 + X$ at the LHC



$p\bar{p} \rightarrow b\bar{b}h^0 + X$ at the Tevatron



from S.Dawson, C.Jackson, L.Reina, D.W., hep-ph/0311067

To a good approximation the MSSM result can be obtained from the SM result as follows:

$$\sigma_{\text{NLO}}(\text{MSSM}) \sim \sigma_{\text{NLO}}(\text{SM}) \left(\frac{g_{bbh}^{\text{MSSM}}}{g_{bbh}} \right)^2$$

Inclusive and semi-inclusive $b\bar{b}$ Higgs production at hadron colliders

For a review see, e.g., J.Campbell *et al.*, LesHouches 2003 proceedings.

Status: There exist two approaches, dubbed *variable (or five) flavor number scheme* (VFS) and *fixed (or four) flavor number scheme* (FFS):

→ FFS approach

Fixed order, explicit matrix element calculation based on the parton level processes $gg, q\bar{q} \rightarrow b\bar{b}h$.

Inclusive (no b tagged) and semi-inclusive (1 b tagged): known at NLO QCD

Two independent calculations by

S.Dittmaier, M.Krämer, M.Spira and S.Dawson, C.Jackson, L.Reina, D.W.

→ These two calculations are in good agreement.

→ VFS approach

Use of b quark PDFs to sum to all orders large logs, $\alpha_s \log(m_b^2/\mu_F^2)$ ($\mu_F \approx M_h$), which arise due to initial-state $g \rightarrow b\bar{b}$ splitting.

→ VFS approach

Inclusive (no b tagged): known at NNLO QCD

b quark fusion, $b\bar{b} \rightarrow h$, is the leading order subprocess of $\mathcal{O}(\alpha_s^2 \log^2(M_h/\mu_b))$ and $b(\bar{b})g \rightarrow b(\bar{b})h$ and $gg, q\bar{q} \rightarrow b\bar{b}h$ are identified as NLO contributions to $b\bar{b} \rightarrow h$ of $\mathcal{O}(1/\ln(M_h/m_b))$ and $\mathcal{O}(1/\ln^2(M_h/m_b))$, respectively.

D.Dicus, F.Maltoni, T.Stelzer, Z.Sullivan, S.Willenbrock

Inclusive $pp, p\bar{p} \rightarrow (b\bar{b})H + X$ production has been calculated at NNLO QCD by R.Harlander, W.Kilgore.

Semi-inclusive (1 b -tagged): known at NLO QCD

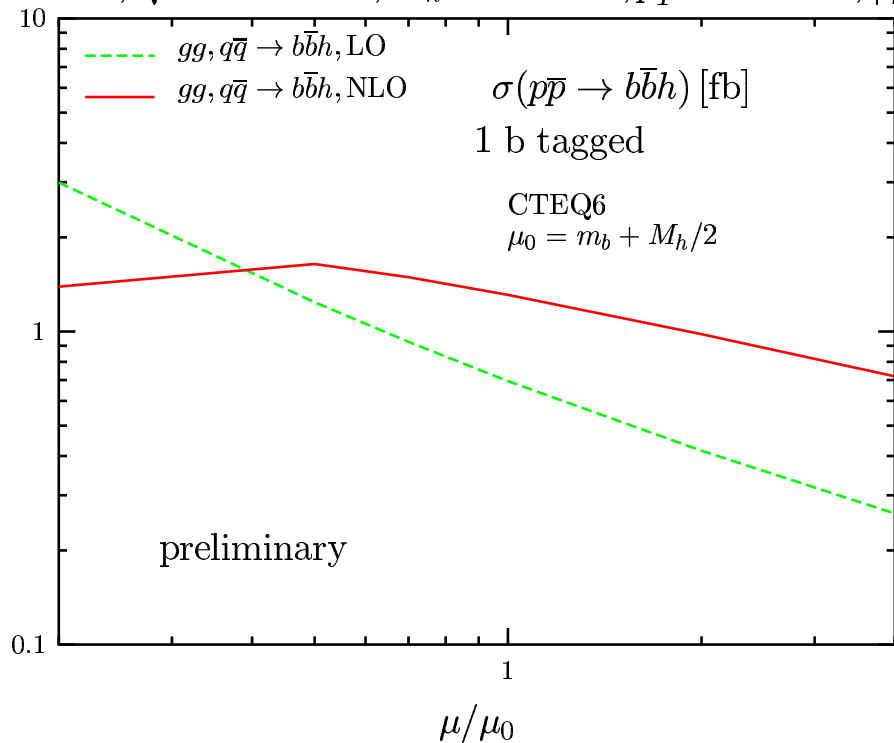
$b(\bar{b})g \rightarrow b(\bar{b})h$ is the leading order subprocess of $\mathcal{O}(\alpha_s^2 \log(M_h/\mu_b))$ and $gg, q\bar{q} \rightarrow b\bar{b}h$ are identified as NLO contributions of $\mathcal{O}(1/\ln(M_h/m_b))$.

J.Campbell, R.K.Ellis, F.Maltoni, S.Willenbrock

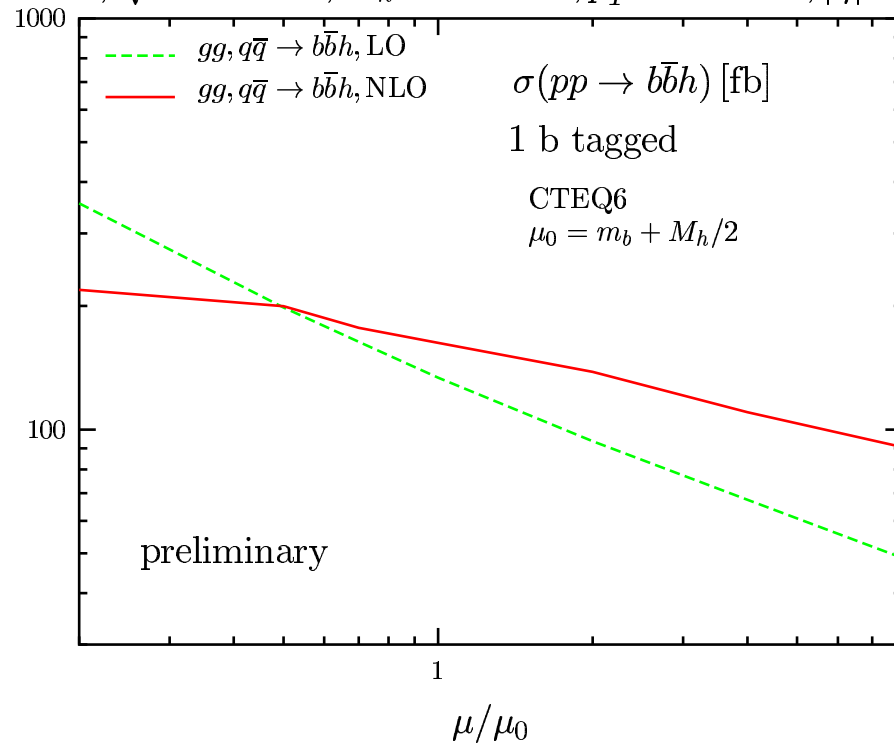
Main Result

Drastically reduced scale dependence of the
NLO QCD cross sections – 1 b tagged:

Tevatron, $\sqrt{s} = 1.96\text{TeV}$, $M_h = 120\text{GeV}$, $p_T^{b/\bar{b}} > 20\text{GeV}$, $|\eta| < 2$



LHC, $\sqrt{s} = 14\text{TeV}$, $M_h = 120\text{GeV}$, $p_T^{b/\bar{b}} > 20\text{GeV}$, $|\eta| < 2.5$

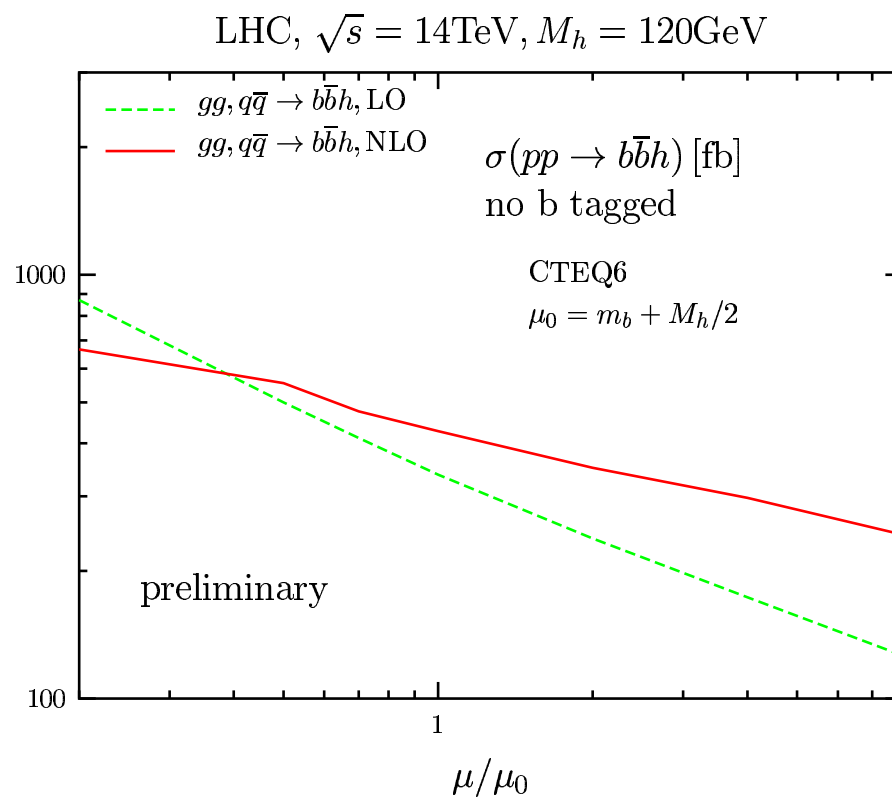
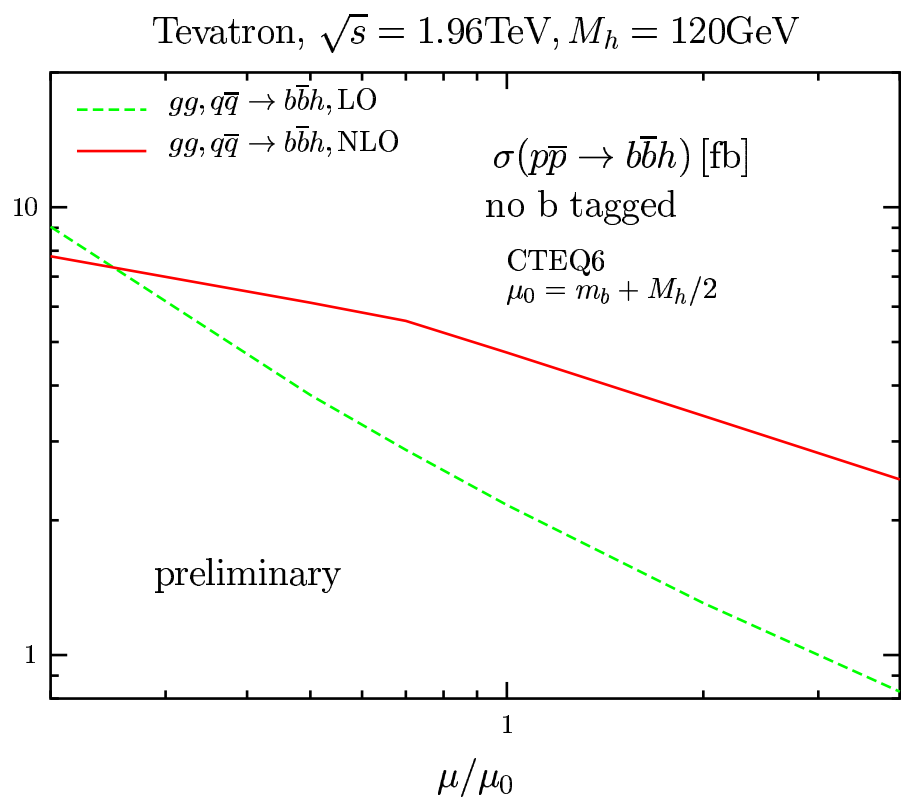


from S.Dawson, C.Jackson, L.Reina, D.W., in preparation

see also S.Dittmaier *et al.*, hep-ph/0309204 and J.Campbell *et al.* in LesHouches 2003 proceedings

Main Result

Drastically reduced scale dependence of the
NLO QCD cross sections – no b tagged:



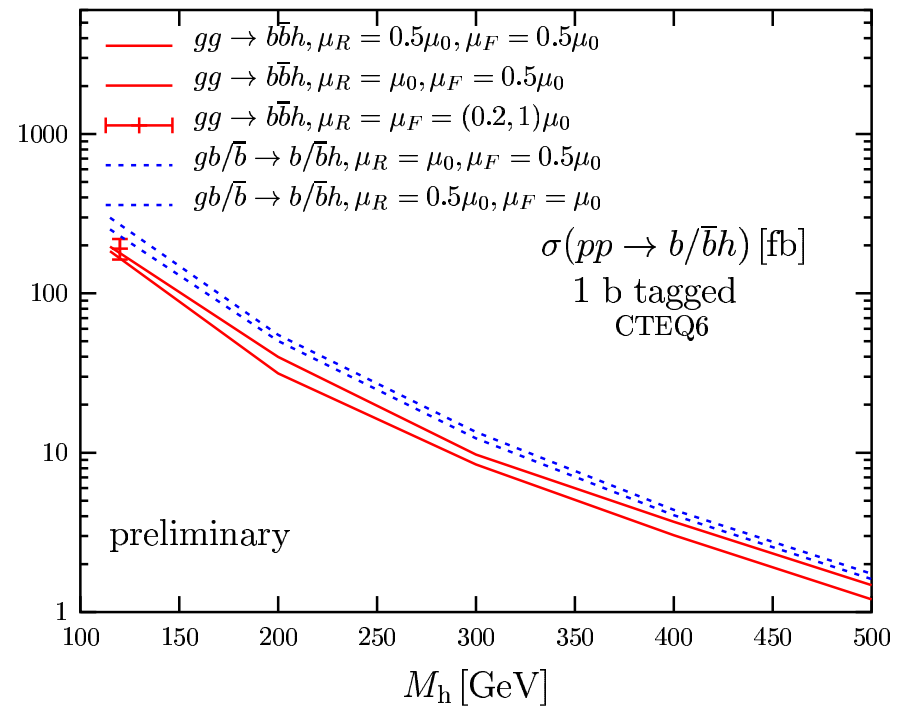
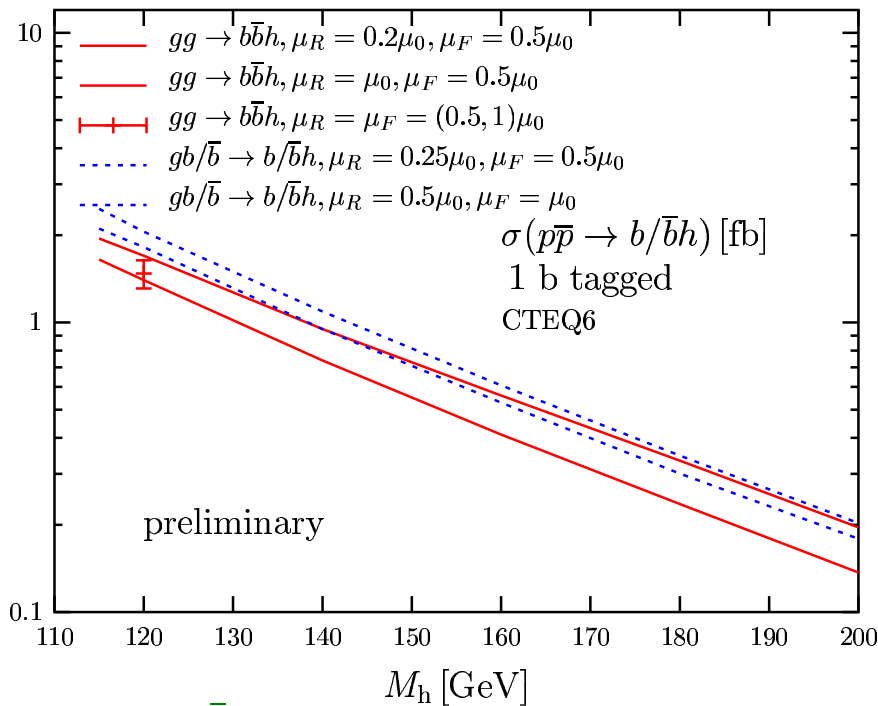
from S.Dawson, C.Jackson, L.Reina, D.W., in preparation

see also S.Dittmaier *et al.*, hep-ph/0309204 and J.Campbell *et al.* in LesHouches 2003 proceedings

M_h dependence – 1 b tagged

Comparison with b quark PDF approach by J.Campbell, R.K.Ellis, F.Maltoni, and S.Willenbrock:

Tevatron, $\sqrt{s} = 1.96\text{TeV}$, $\mu_0 = m_b + M_h/2$, $p_T^{b/\bar{b}} > 20\text{GeV}$, $|\eta| < 2$ LHC, $\sqrt{s} = 14\text{TeV}$, $\mu_0 = m_b + M_h/2$, $p_T^{b/\bar{b}} > 20\text{GeV}$, $|\eta| < 2.5$

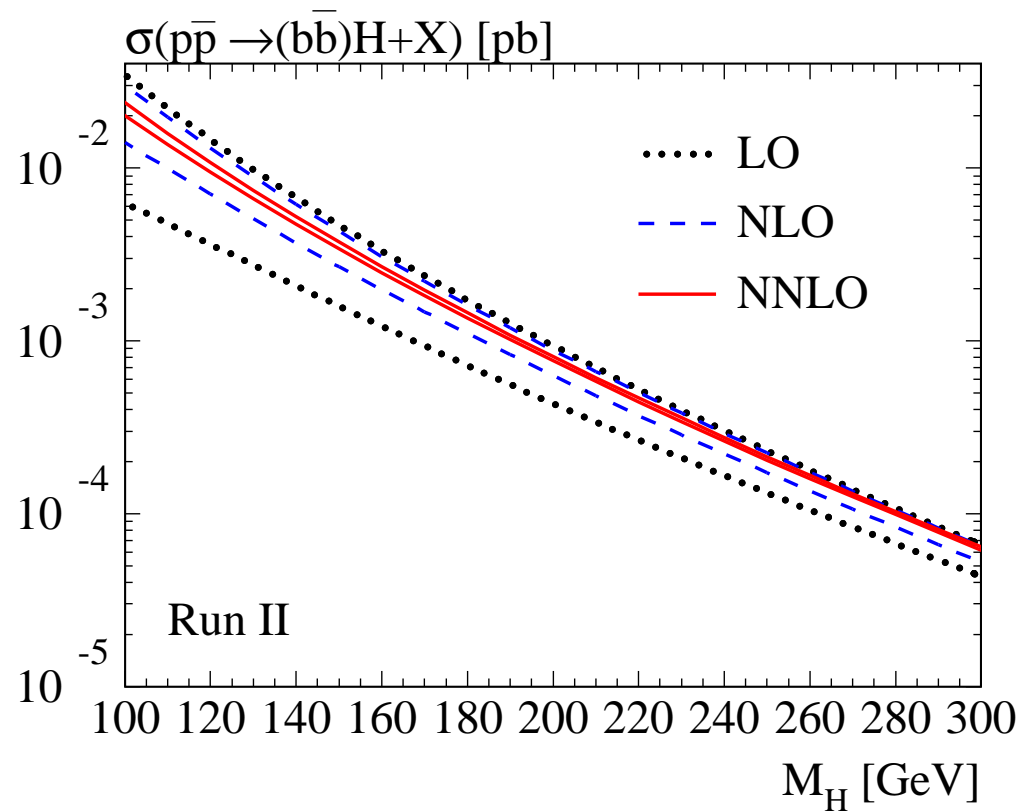
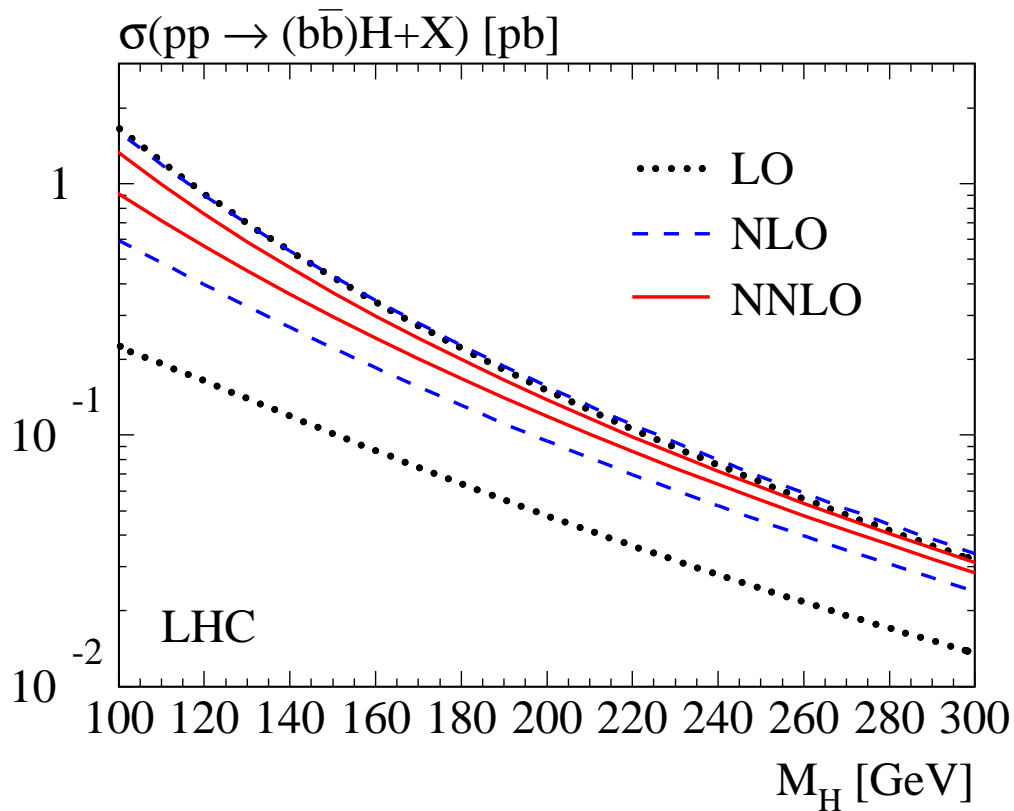


$gg, q\bar{q} \rightarrow b\bar{b}h$: from S.Dawson, C.Jackson, L.Reina, D.W., in preparation, see also S.Dittmaier *et al.*, hep-ph/0309204
 $gb(\bar{b}) \rightarrow b(\bar{b})h$: from J.Campbell *et al.* in LesHouches 2003 proceedings, see also J.Campbell *et al.*, PRD67 095002 (2003)

NOTE: $gg, q\bar{q} \rightarrow b\bar{b}h$ scale uncertainty band is underestimated ! Scale dependence is expected to be larger when varying μ_F and $\mu_F \neq \mu_R$ (see, e.g., error bars at $M_h = 120$ GeV).

M_h dependence – 0 b tagged (VFS)

from R.Harlander, W.Kilgore, Phys.Rev. D68 (2003) 013001



$$\mu_F = (0.1, 0.7)M_h, \mu_R = M_h$$

Summary

- $b\bar{b}h$ is an important Higgs production mode in models with an enhanced b quark Yukawa coupling, e.g. for large values of $\tan\beta$ in the 2HDM, MSSM.
- It is crucial to know the impact of QCD corrections.
- There has been considerable improvement in obtaining stable QCD predictions for inclusive, semi-inclusive and exclusive Higgs production in association with b quarks (for a review see, e.g., J.Campbell *et al.*, LesHouches 2003 proceedings):
 - In all three cases, at NLO (NNLO) QCD the factorization/renormalization scale dependence is strongly reduced.
 - $p\bar{p}, pp \rightarrow b\bar{b}h$ production has been calculated at NLO QCD based on the $gg, q\bar{q} \rightarrow b\bar{b}h$ parton level processes independently by two groups:
 - The two calculations are in good agreement.
 - Results have been obtained for the inclusive, semi-inclusive and exclusive case.

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- In the exclusive case (2 b-tagged), the remaining theoretical uncertainty is estimated to be about 15 – 20% (Tevatron,LHC) due to residual scale dependence and about 15 – 20% (Tevatron,LHC) due to b quark Yukawa coupling renormalization scheme dependence.
- Semi-inclusive $b(\bar{b})h$ production based on $b(\bar{b})g \rightarrow b(\bar{b})h$ has been calculated at NLO QCD using the b quark PDF approach (VFS).
 - The two NLO calculations, based on $gg, q\bar{q} \rightarrow b\bar{b}h$ (FFS) and $gb(\bar{b}) \rightarrow b(\bar{b})h$ (VFS) subprocesses, agree within their respective theoretical uncertainties.
 - Inclusive $(b\bar{b})h$ production based on b quark fusion, $b\bar{b} \rightarrow h$, is known at NNLO QCD (VFS).
 - Possible improvement (FFS): Identification and resummation of large logarithms, $\log(M_h/m_b)$, arising when integrating over the b quark p_T .