TeV4LHC Workshop BNL, February 4, 2005

b quarks and Higgs Physics at Hadron Colliders

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

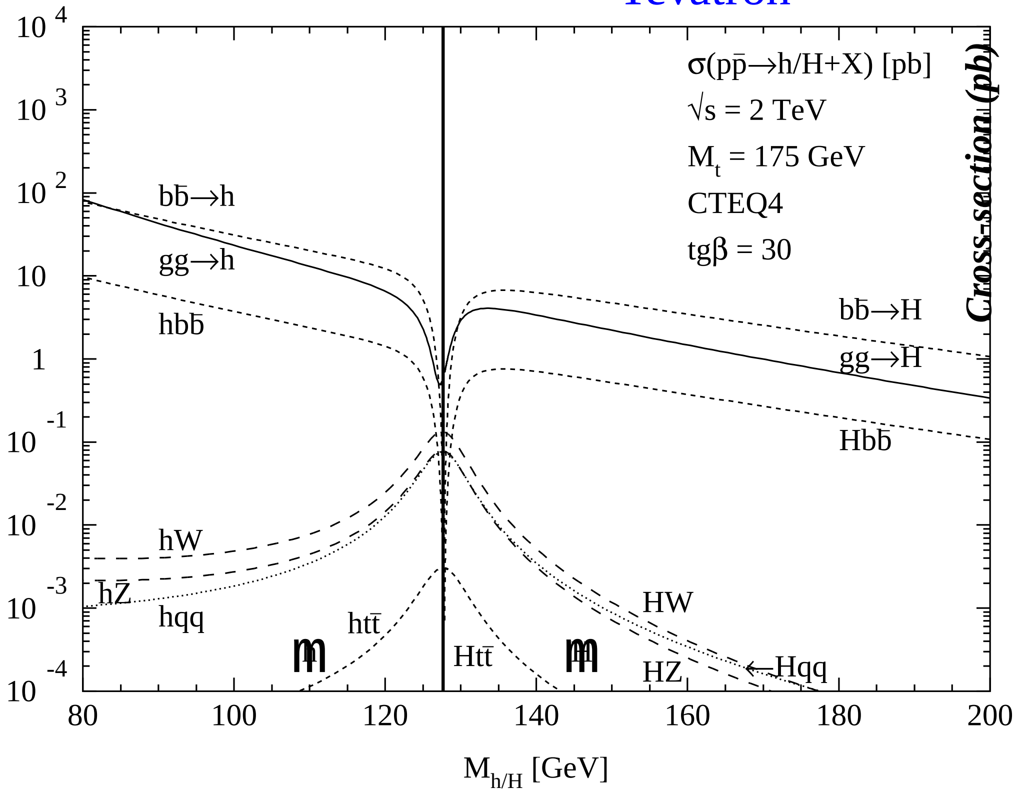
In the MSSM, however, the cross sections to $p\bar{p}, pp \to b\bar{b}\Phi^0$, $\Phi^0 = h^0, H^0, A^0$, are enhanced with respect to the SM for large values of $\tan\beta$:

$g^{MSSM}_{ff\phi^0}/g_{ffH}$	h^0, H^0	A^0
$I_3^f = -1/2$ $f = b, \mu, \tau, \ldots$	$\frac{(-\sin\alpha, \cos\alpha)}{\cos\beta}$	$\tan\beta$
$I_3^f = 1/2$ $f = t, \ldots$	$\frac{(\cos\alpha, \sin\alpha)}{\sin\beta}$	$\cot\beta$

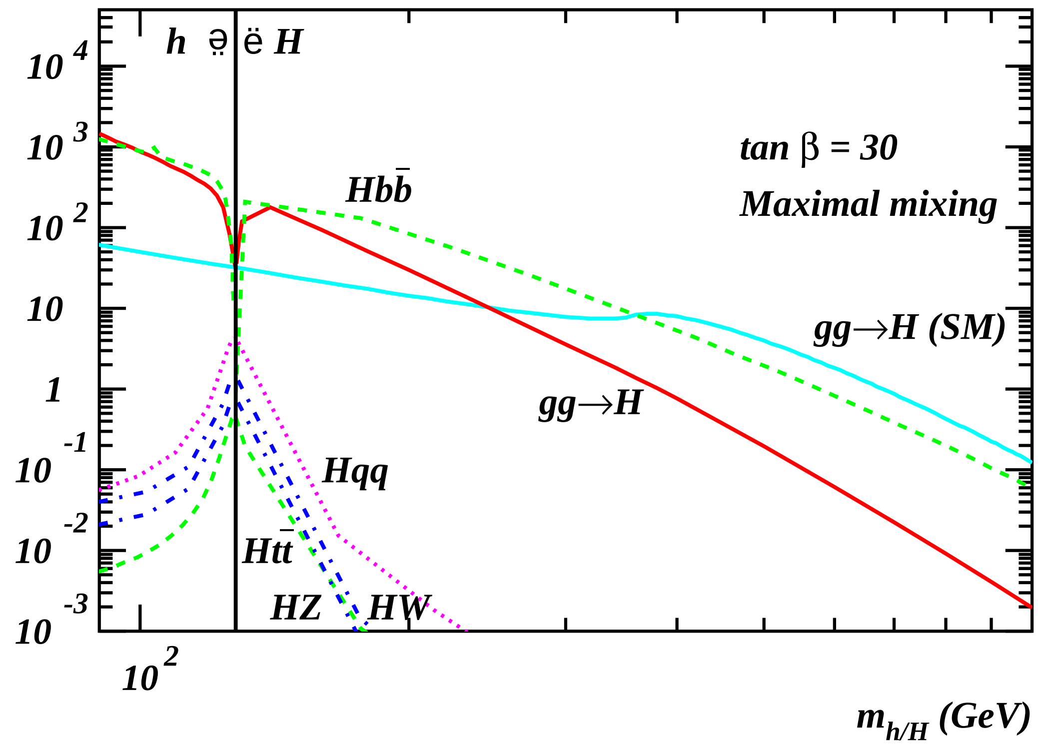
At $\tan\beta = 40$, for instance, the $b\bar{b}(h^0, H^0, A^0)$ coupling can be as strong as the SM $t\bar{t}H$ coupling.

At large $\tan\beta$ Higgs boson production in association with b quarks becomes the dominant neutral MSSM Higgs production mode:

Tevatron



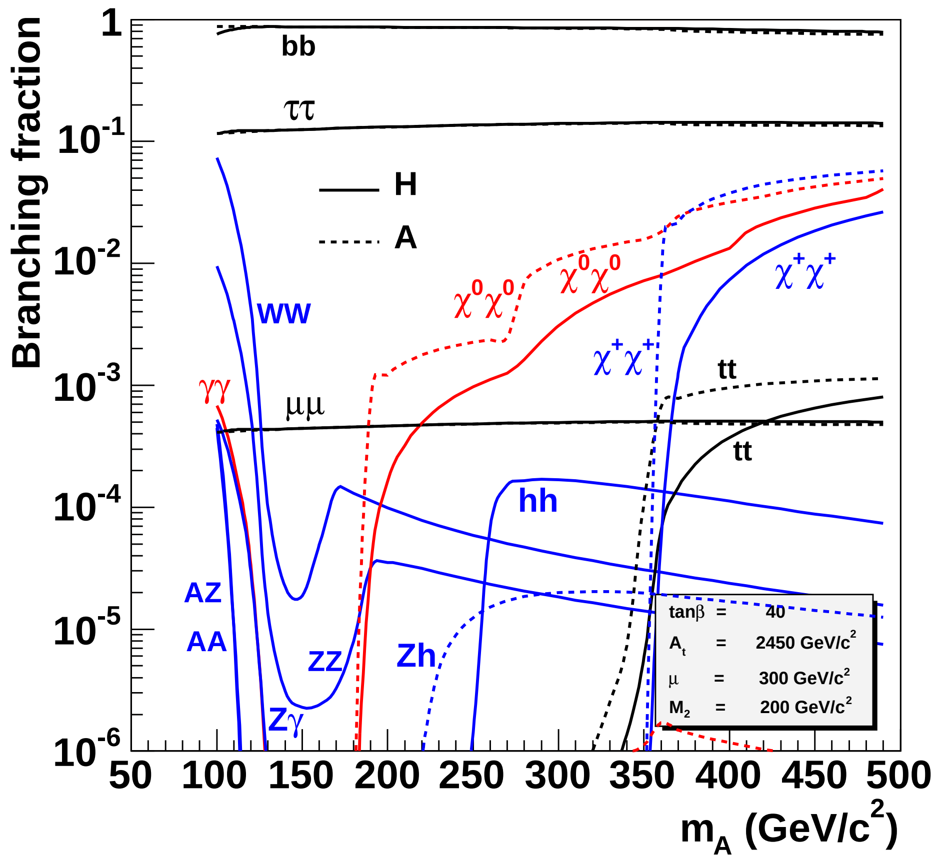
LHC



from M.Carena, H.Haber, Prog.Part.Nucl.Phys.50 (2003)

M.Spira, Fortschr.Phys.46 (1998) and hep-ph/9810289 (update)

Branching ratios for the MSSM neutral Higgs bosons, H^0 and A^0, at large $\tan\beta$:



A.Djouadi, J.Kalinowski and M.Spira, HDECAY, hep-ph/9704448

taken from R.Kinnunen, CMS-CR-2004-058

Most studies use the LEP setup:

$M_2 = 200\,\text{GeV}, \mu = -200\,\text{GeV}$

$M_{\tilde{g}} = 800\,\text{GeV}, M_{\tilde{q},\tilde{l}} = 1\,\text{TeV}$

$\Rightarrow$ no Φ^0 decay to sparticles

and at large $\tan\beta$ only

$\Phi^0 \to b\bar{b}, \tau\tau, \mu\mu$ decays are considered

LHC H^0, A^0 discovery potential using sparticle decay modes: see, e.g., F.Moortgat *et al*, hep-ph/0112046

Higgs boson production in association with b quarks in the MSSM is an important production mode for

- discovery of $\Phi^0 = h^0, H^0, A^0$,
- measurement of Φ^0 masses and $\tan\beta$,
- obtaining information about b quark and τ, μ Yukawa couplings.

Production modes:

$b\bar{b} \to \Phi^0$: fully inclusive, no b quark identified

LHC: only through$\Phi^0 \to \tau\tau, \mu\mu$,

since QCD multijet background to $\Phi^0 \to b\bar{b}$ too large

$bg \to b\Phi^0, \bar{b}g \to \bar{b}\Phi^0$: semi-inclusive,

one $b(\bar{b})$ quark identified

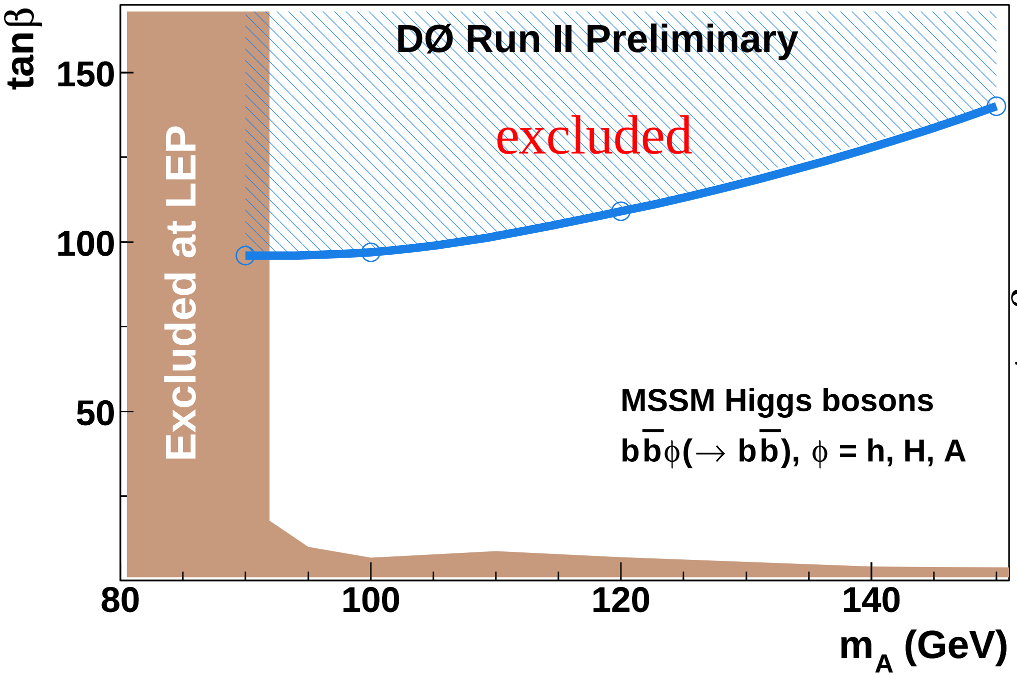
$gg, q\bar{q} \to b\bar{b}\Phi^0$: exclusive,

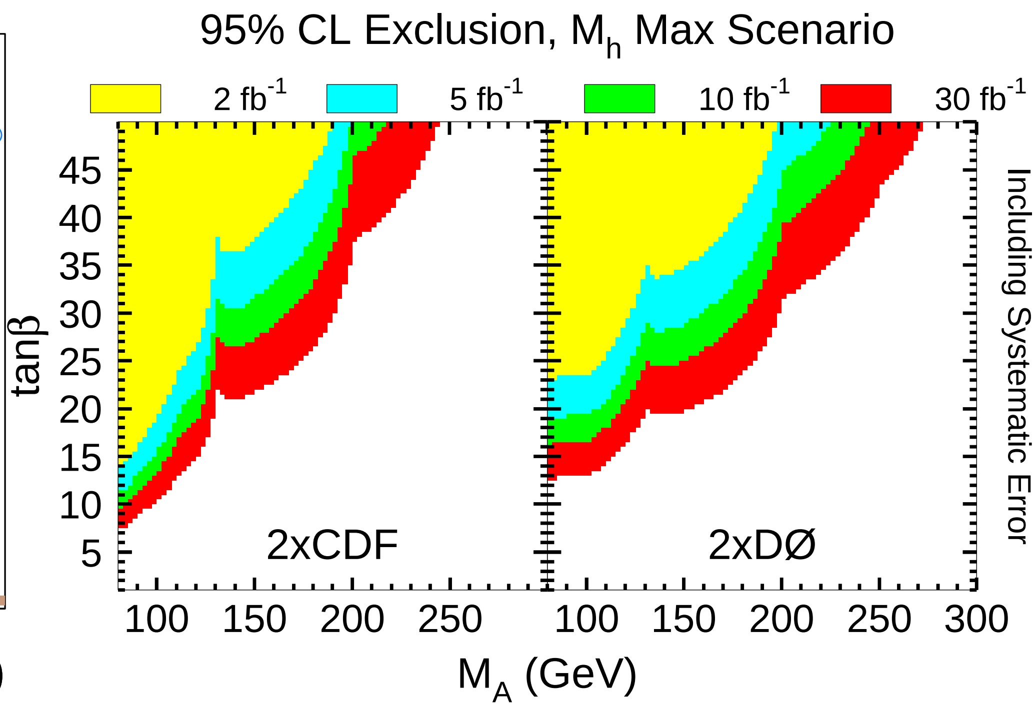
two b quarks identified

} measures unambiguously the b Yukawa coupling, $\sigma \propto g^2_{bb\Phi^0}$(at tree level)

Tevatron MSSM neutral Higgs discovery potential

Search for MSSM $h = H^0, h^0, A^0$ in 3 b-tagged events using D0 Run II data (left) and Tevatron 95 % CL exclusion contours for $b\bar{b}h \to b\bar{b}b\bar{b}$ (right):





from The D0 collaboration, D0 Note 4366 - CONF

see also talk by S.M.Wang, Moriond 2004

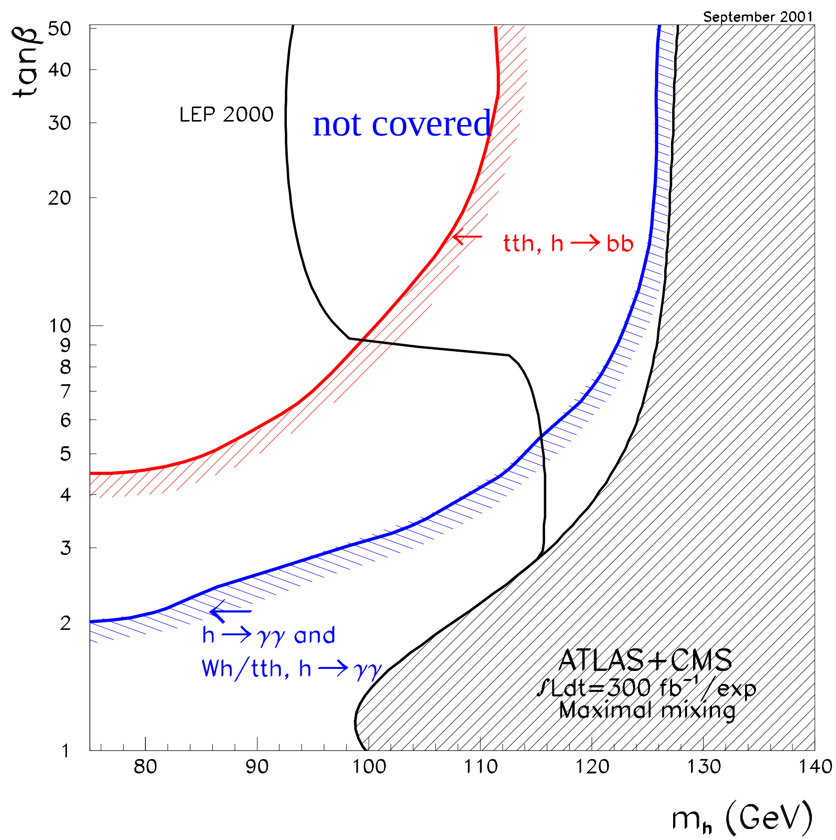
from the Report of the Tevatron Higgs WG, hep-ph/0010338

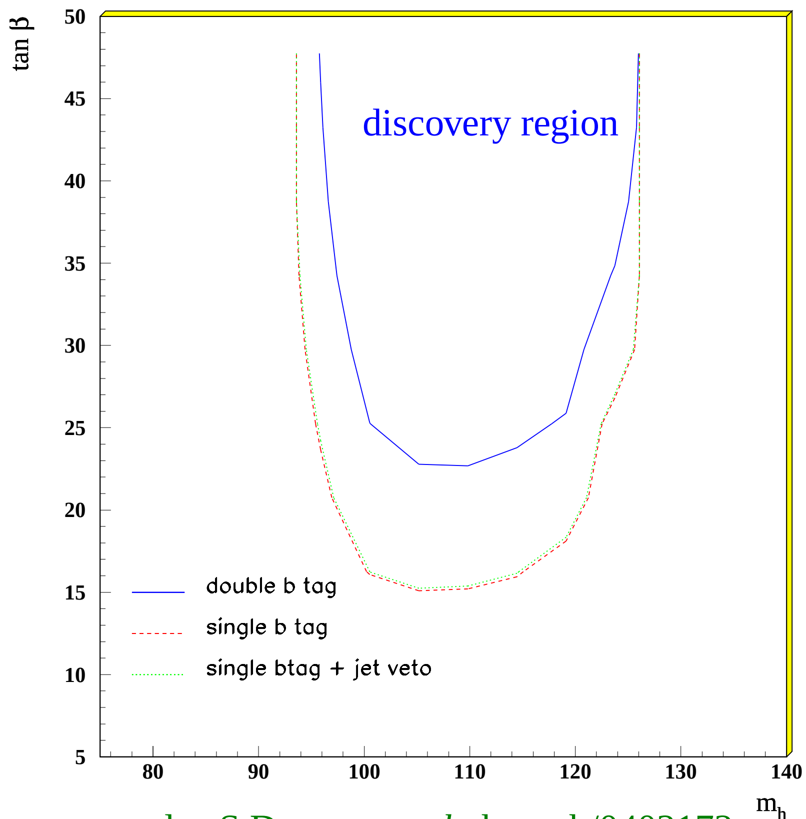
CDF: Search for $\phi^0 \to \tau\tau$ in inclusive Higgs production: see talk by W.Yao, ICHEP04

LHC MSSM neutral Higgs discovery potential

Sensitivity for a MSSM light Higgs (h^0) boson discovery (left) and the discovery potential for $b\bar{b}h^0$ with $h^0 \to \mu^+\mu^-$ (right) (5σ curves):

$$g_{bbh^0}^{MSSM} = \frac{(-\sin\alpha)}{\cos\beta}\, g_{bbH} \quad \text{and} \quad g_{tth^0}^{MSSM} = \frac{\cos\alpha}{\sin\beta}\, g_{ttH}$$



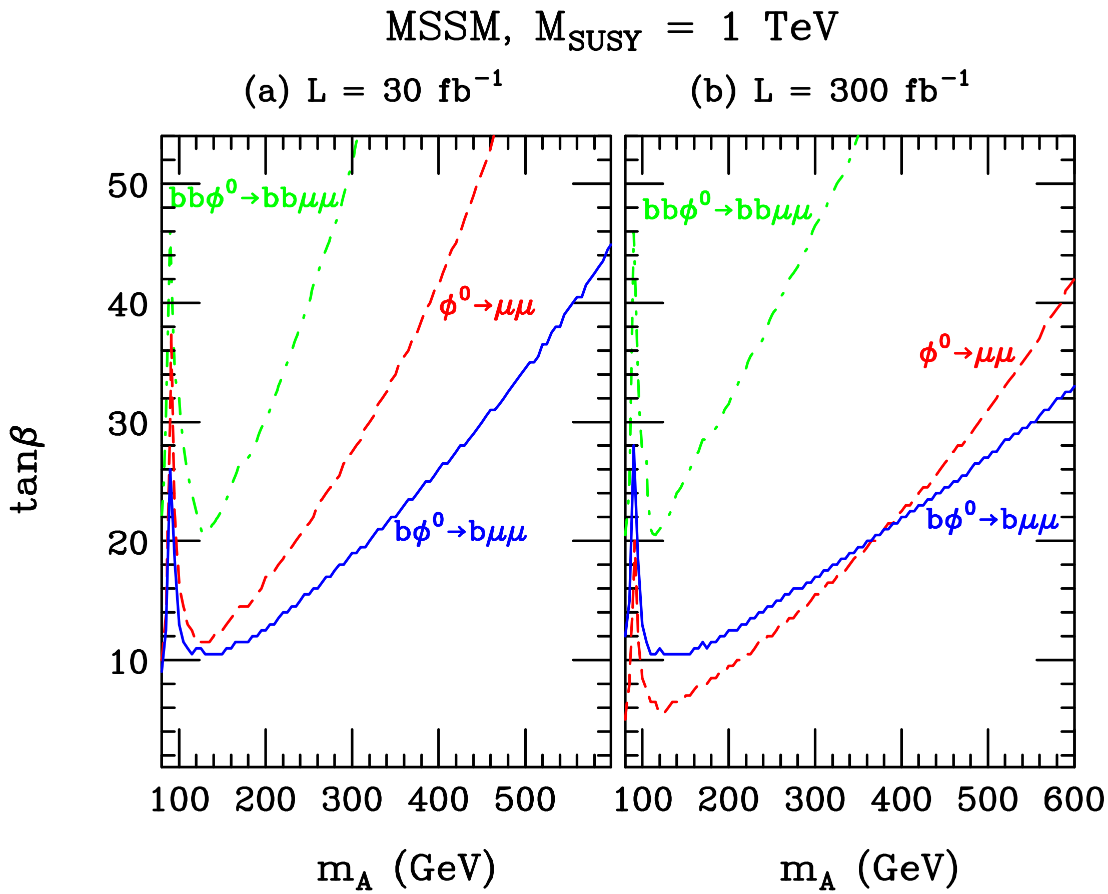


see also S.Dawson *et al.*, hep-ph/0402172

from S.Gentile, ATL-PHYS-2004-009 (and references therein)

LHC MSSM neutral Higgs discovery potential

Discovery potential for $b\bar{b}\Phi^0$ with $\Phi^0 \to \mu^+\mu^-$ (right) (5σ curves):



from S.Dawson, D.Dicus, C.Kao, R.Malhotra, PRL92 (2004), hep-ph/0402172

→ includes A^0, h^0 signal for $M_A < 125$ GeV

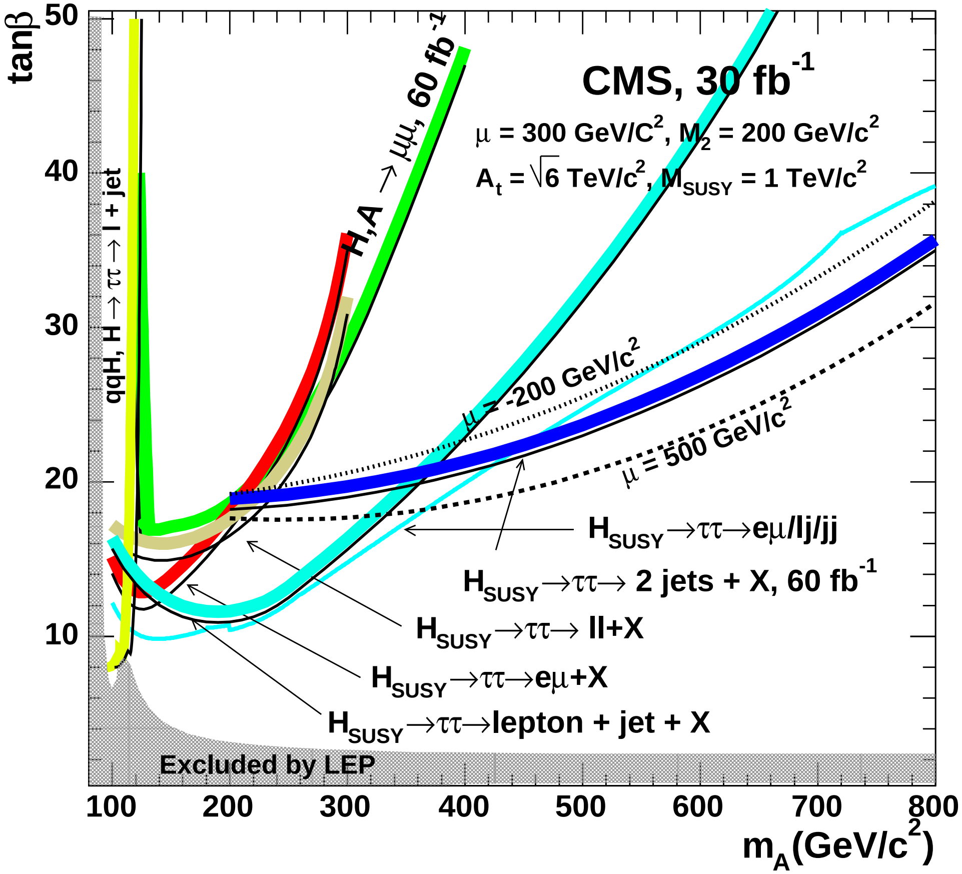
→ includes A^0, H^0 signal for $M_A > 125$ GeV

$b\Phi^0 \to b\mu\mu$ considerably extends the discovery region beyond the inclusive channel $\Phi^0 \to \mu\mu$

see also $h^0 \to \tau\tau$ study by, e.g.,
E.Richter-Was *et al.*, PLB589 (2004), hep-ph/040215

LHC MSSM neutral Higgs discovery potential

Discovery potential for the MSSM heavy Higgs bosons, $gg \to b\bar{b}(H^0, A^0)$ with $H^0, A^0 \to \tau\tau, \mu\mu$ (5σ curves):

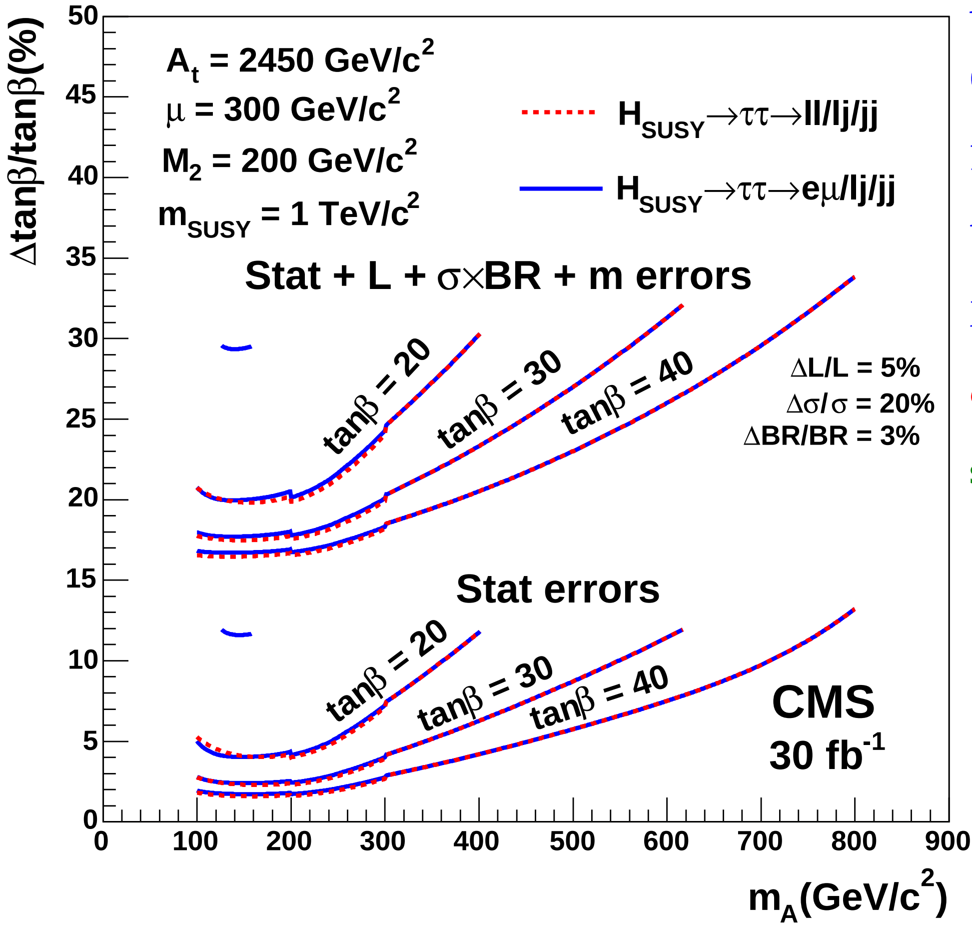


Discovery reach for $gb \to b\Phi^0 \to b\tau\tau$?

from R.Kinnunen *et al.*, The Higgs working group: Summary report, hep-ph/0406152

Measurement of $\tan\beta$ at the LHC

Uncertainty of the $\tan\beta$ measurement for $gg \to b\bar{b}(H^0, A^0) \to b\bar{b}\tau\tau$:



Additional SUSY parameter dependence enters through radiative corrections but for large $\tan\beta$ the replacement $\tan\beta \to \tan\beta_{eff}$ in the b Yukawa coupling is a good approximation and:

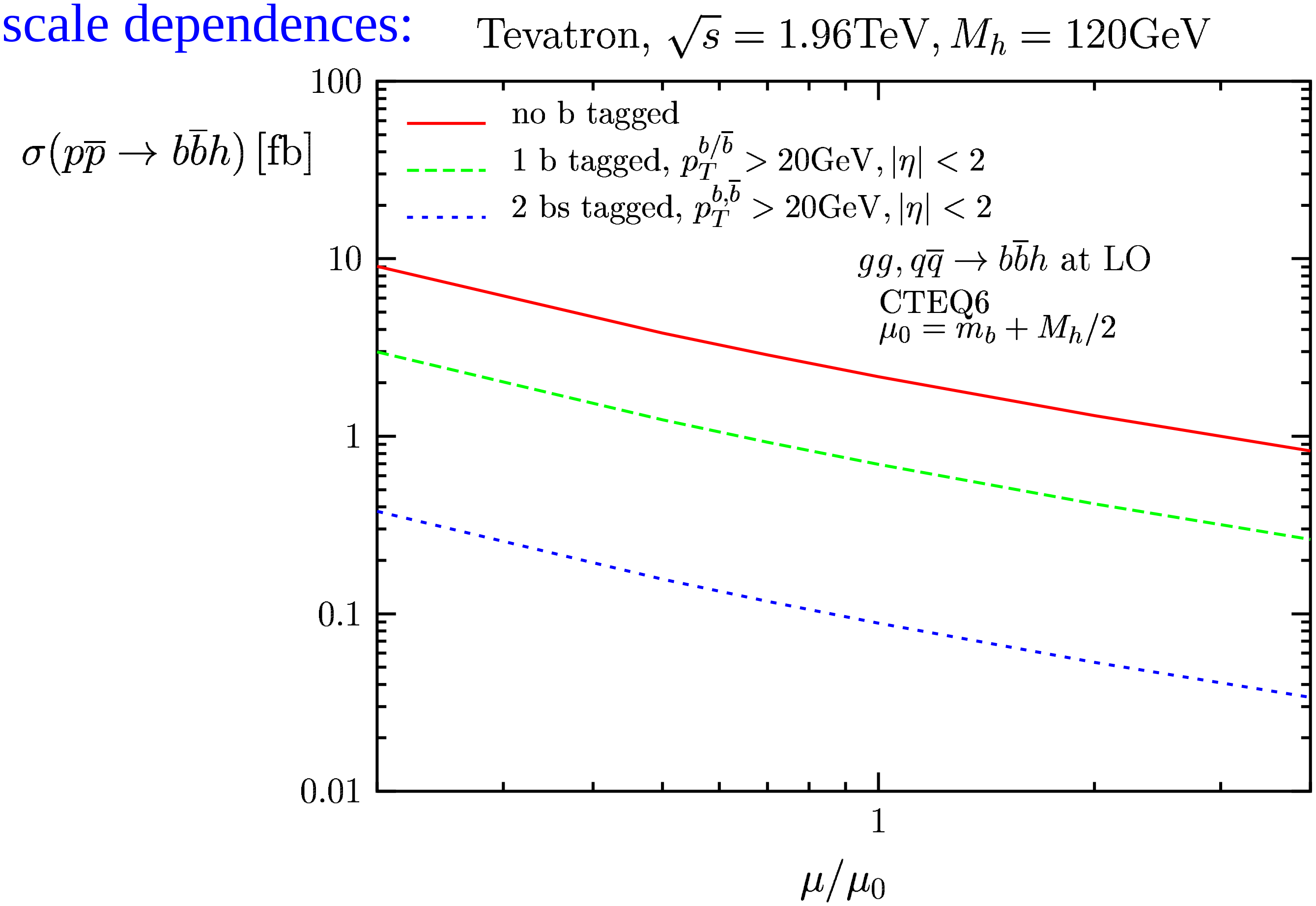
$\sigma(gg \to b\bar{b}\Phi^0) \propto \tan\beta^2_{eff}$

see, e.g., M.Carena *et al.*, hep-ph/0208209

from R.Kinnunen *et al.*, The Higgs working group: Summary report, hep-ph/0406152

Need for NLO QCD calculations

- LO calculations have very strong renormalization/factorization scale dependences:



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

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

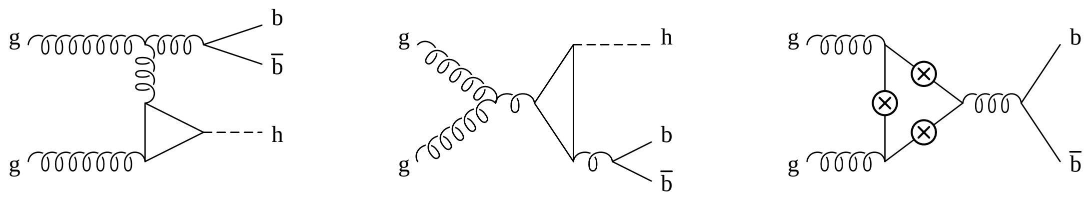
$gg, q\bar{q} \to b\bar{b}h$ at pp and $p\bar{p}$ colliders is dominated by the gg initiated process.

The calculation of the $\mathcal{O}(\alpha_s)$ corrections to $gg, q\bar{q} \to b\bar{b}h$ is technically similar to $t\bar{t}h$ production. We "simply" replace m_t by m_b.

However, there are differences:

→ We consider both the OS scheme and the $\overline{MS}$ scheme when renormalizing the b quark mass in the b Yukawa coupling:
OS: $g_{bbh} = m_b/v$ with m_b being the pole mass
$\overline{MS}$: $g_{bbh} = \overline{m}_b(\mu)/v$ with $\overline{m}_b(\mu)$ being the running mass ⇒ Possible improvement of perturpative calculation by resumming large logarithmic contributions to the $b\bar{b}h$ vertex.

→ The contribution from the closed top quark loops is included, e.g.:



The $b\bar{b}h$ processes are classified according to how many b quarks are identified: 2 b quarks tagged, 1 b quark tagged and the fully inclusive case.

In the 2(1) b-tag case we require two(one) high p_T b quark jets in the final state:

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

Moreover, 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.

New D0 cuts:

$$p_T^{b,\bar{b}} > 15 \text{ GeV} \;\; \text{and} \;\; |\eta_{b,\bar{b}}| < 2.5$$

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

→ Requiring two high p_T b quark jets in the final state reduces the signal, but also greatly reduces the background.

→ Unambiguously proportional to the b quark Yukawa coupling.

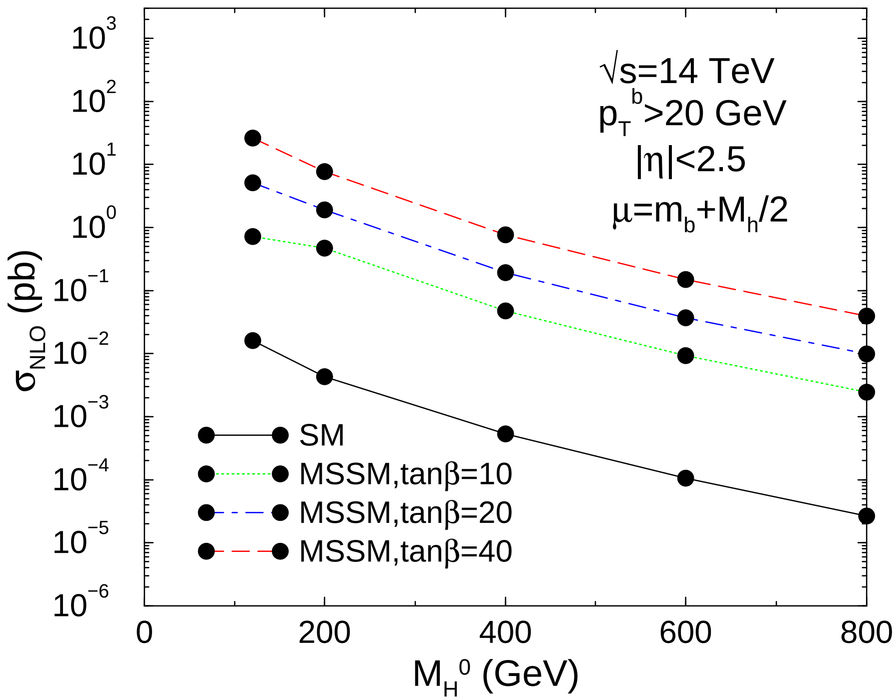
Status:

Two independent calculations based on $gg, q\bar{q} \to b\bar{b}h$ at NLO QCD by S.Dittmaier, M.Krämer, M.Spira (PRD 70 (2004)) and S.Dawson, C.Jackson, L.Reina, D.W. (PRD 69 (2004)).

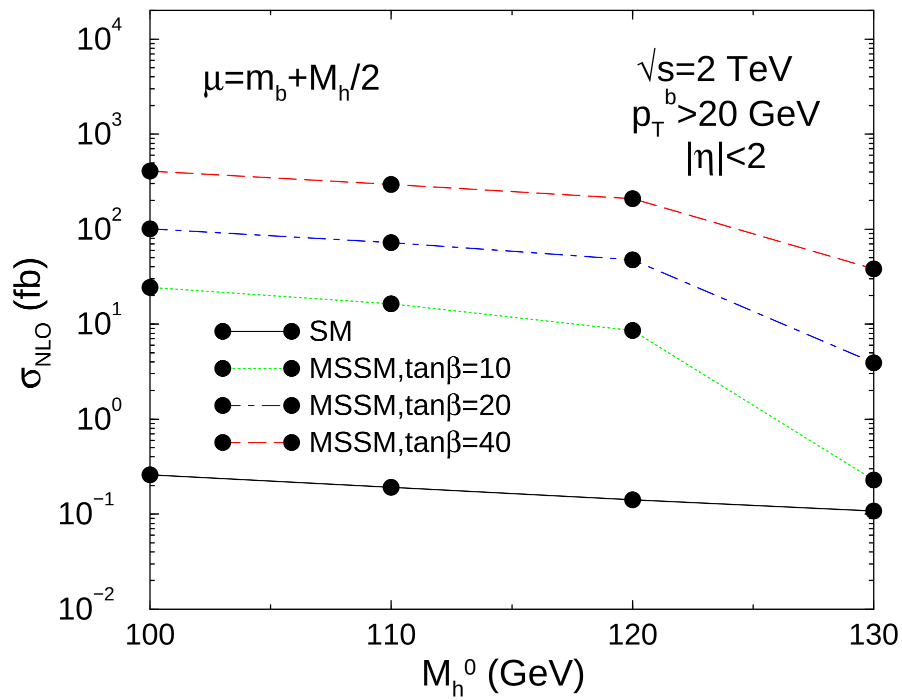
The results of these two calculations are in good numerical agreement.

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

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



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



from S.Dawson, C.Jackson, L.Reina, D.W., PRD 69 (2004)

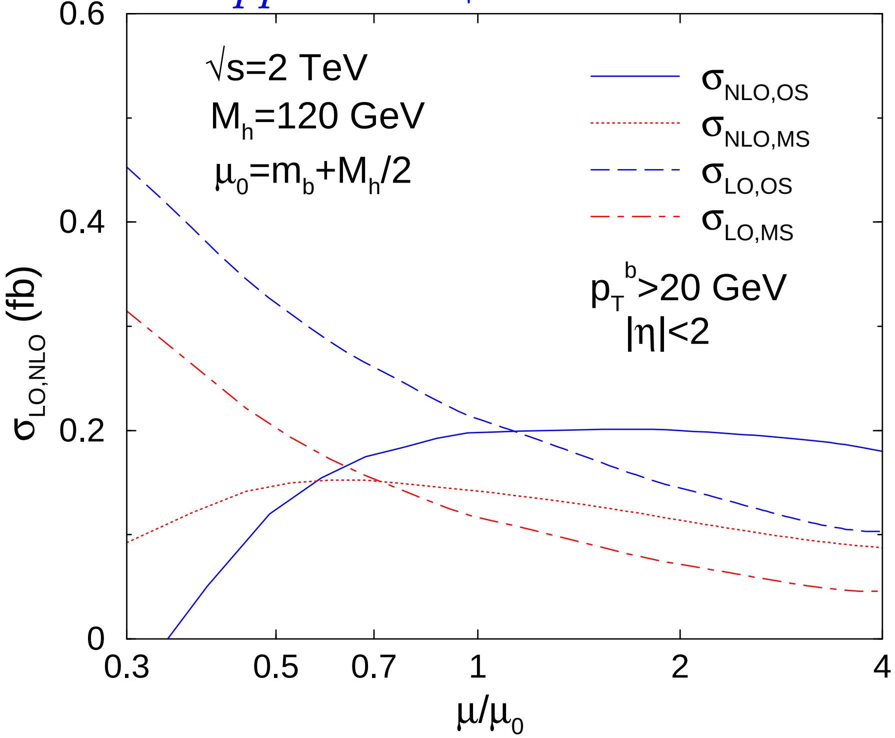
To a good approximation the MSSM result can be obtained from the SM result as follows:

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

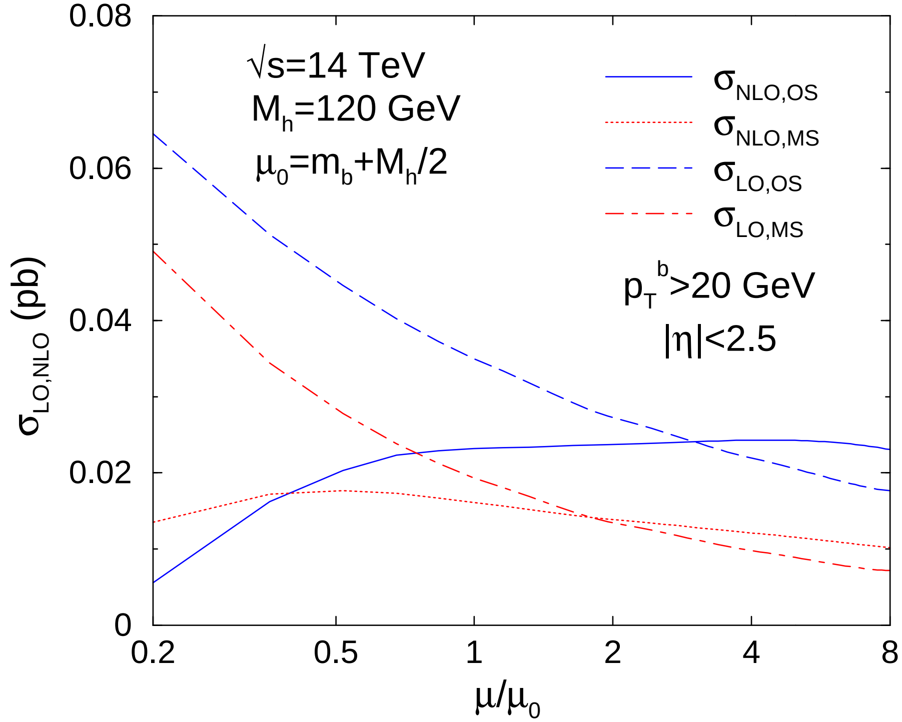
Main Result

Drastically reduced scale dependence of the NLO QCD cross sections:

$p\bar{p} \to b\bar{b}h + X$ at the Tevatron



$pp \to b\bar{b}h + X$ at the LHC

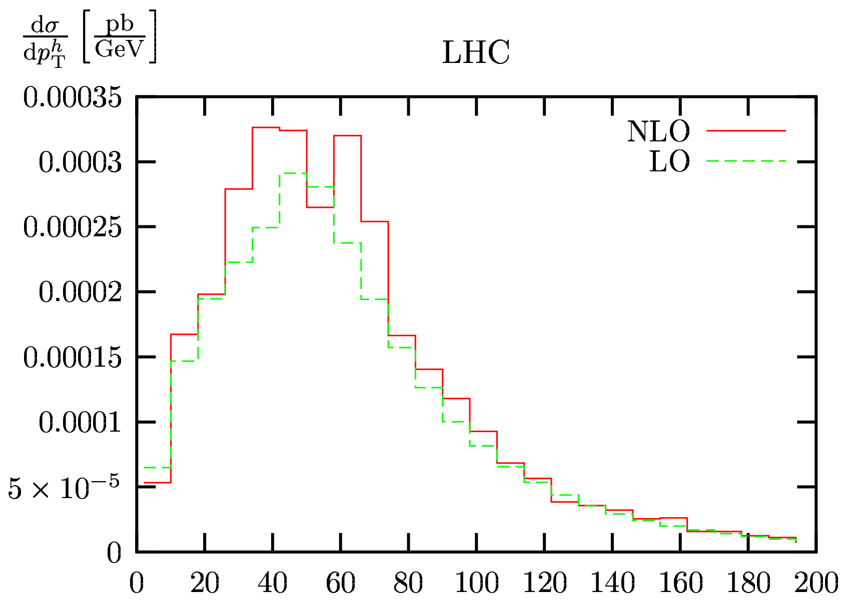


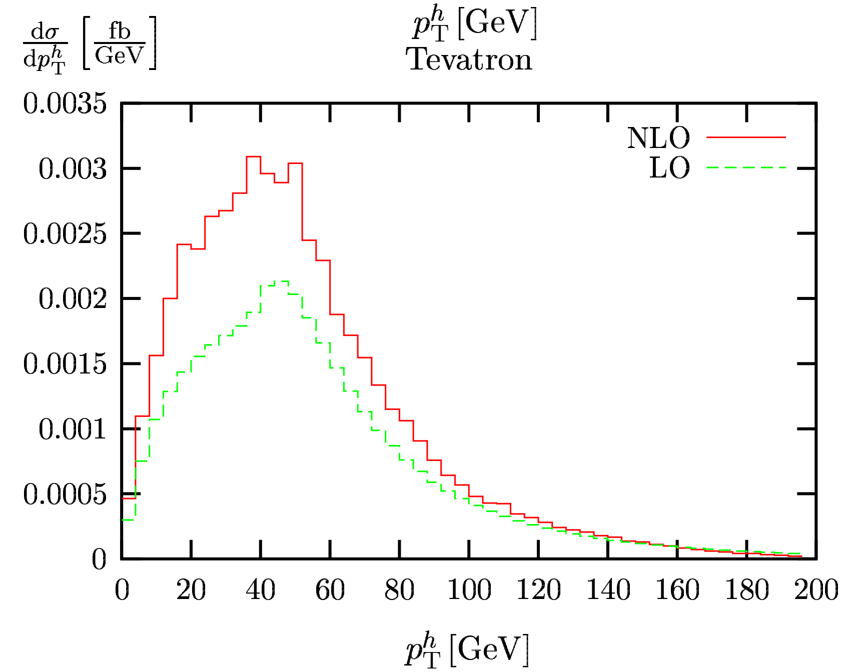
from S.Dawson, C.Jackson, L.Reina, D.W., PRD 69 (2004)

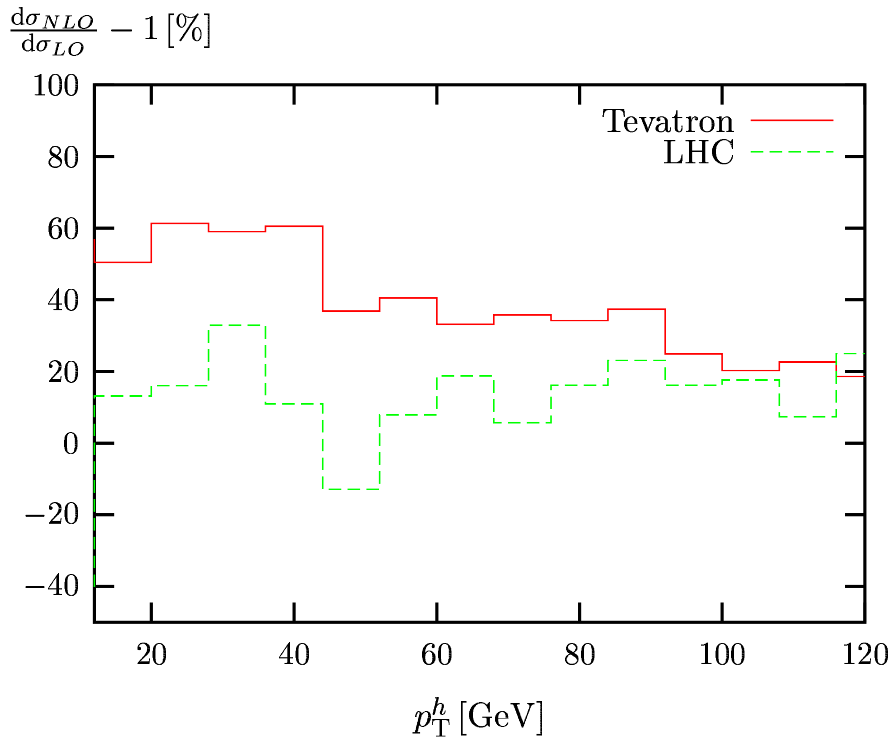
see also S.Dittmaier *et al.*, PRD 70 (2004), and J.Campbell *et al.* in LesHouches 2003 proceedings, hep-ph/0405302

The b quark mass used in g_{bbh} is renormalized either in the on-shell (OS) or $\overline{MS}$ scheme ($\overline{MS}$: LO with 1-loop and NLO with 2-loop running mass).

Effect of NLO QCD corrections on the Higgs p_T distribution:







from S.Dawson, C.Jackson, L.Reina, D.W., PRD 69 (2004)

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, hep-ph/0405302.

Status: There exist two approaches, dubbed *five flavor number scheme* (5FNS) and *four flavor number scheme* (4FNS):

$\rightarrow$ 4FNS 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

Two independent calculations by S.Dittmaier, M.Krämer, M.Spira and S.Dawson, C.Jackson, L.Reina, D.W.

$\rightarrow$These two calculations are in good numerical agreement.

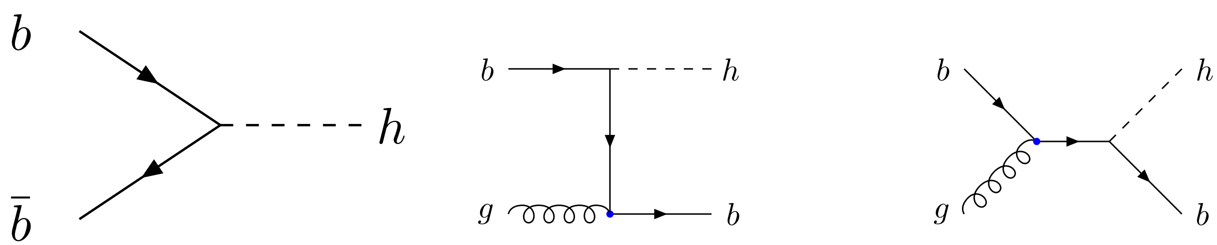
$\rightarrow$ 5FNS approach

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

→ 5FNS approach

Inclusive (no b tagged): known at NNLO QCD

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



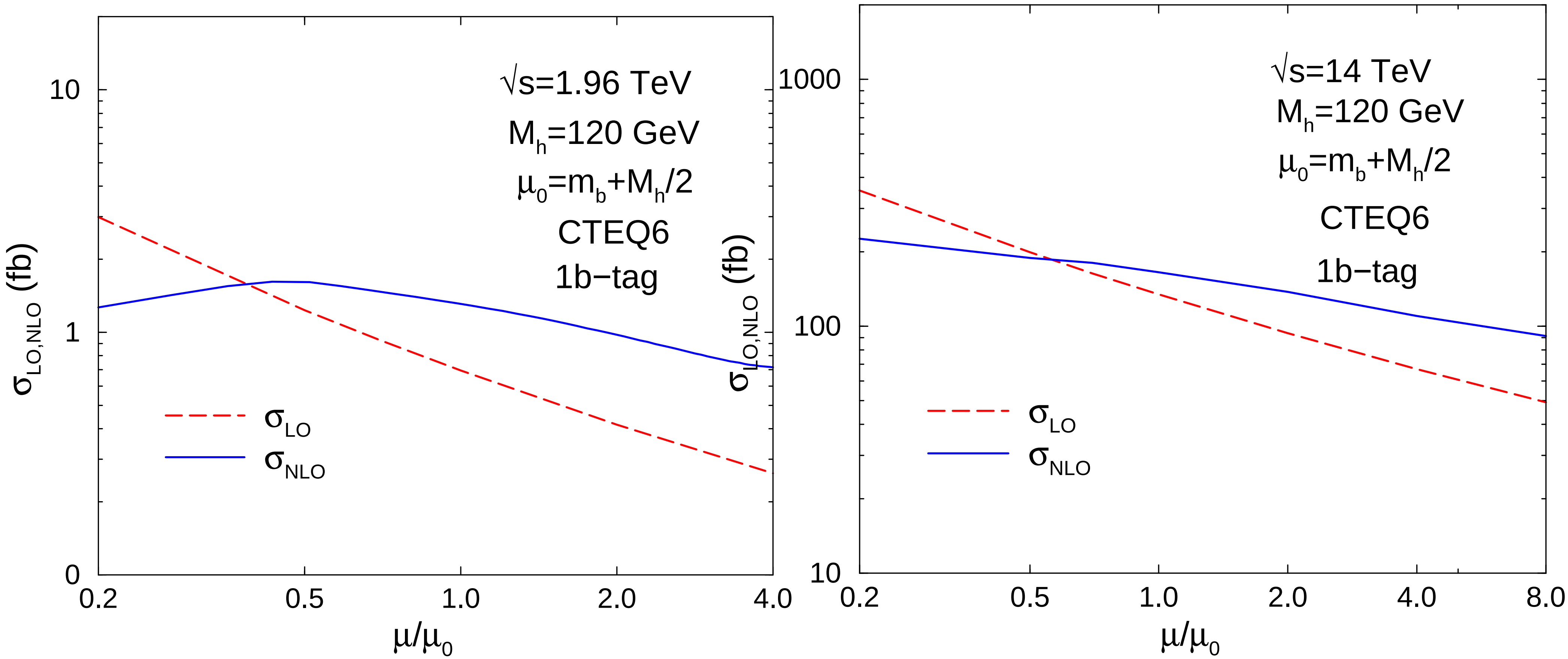
Inclusive $pp, p\bar{p} \to (b\bar{b})H + X$ production has been calculated at NNLO QCD by R.Harlander, W.Kilgore.

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

$b(\bar{b})g \to b(\bar{b})h$ is the leading order subprocess of $\mathcal{O}(\alpha_s^2 \ln(M_h/m_b))$ and $gg, q\bar{q} \to b\bar{b}h$ 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:

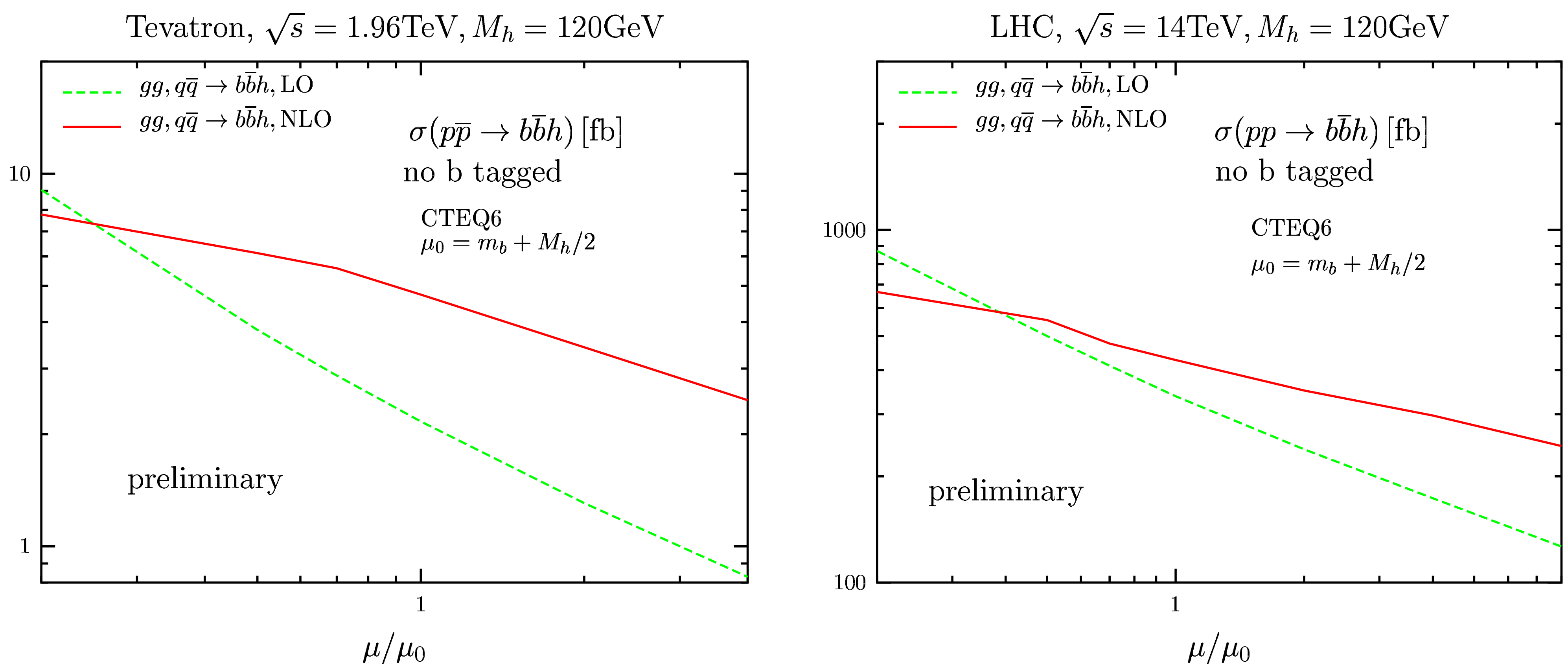


from S.Dawson, C.Jackson, L.Reina, D.W., hep-ph/0408077

see also S.Dittmaier *et al.*, PRD 70 (2004), and J.Campbell *et al.* in LesHouches 2003 proceedings, hep-ph/0405302

Main Result

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

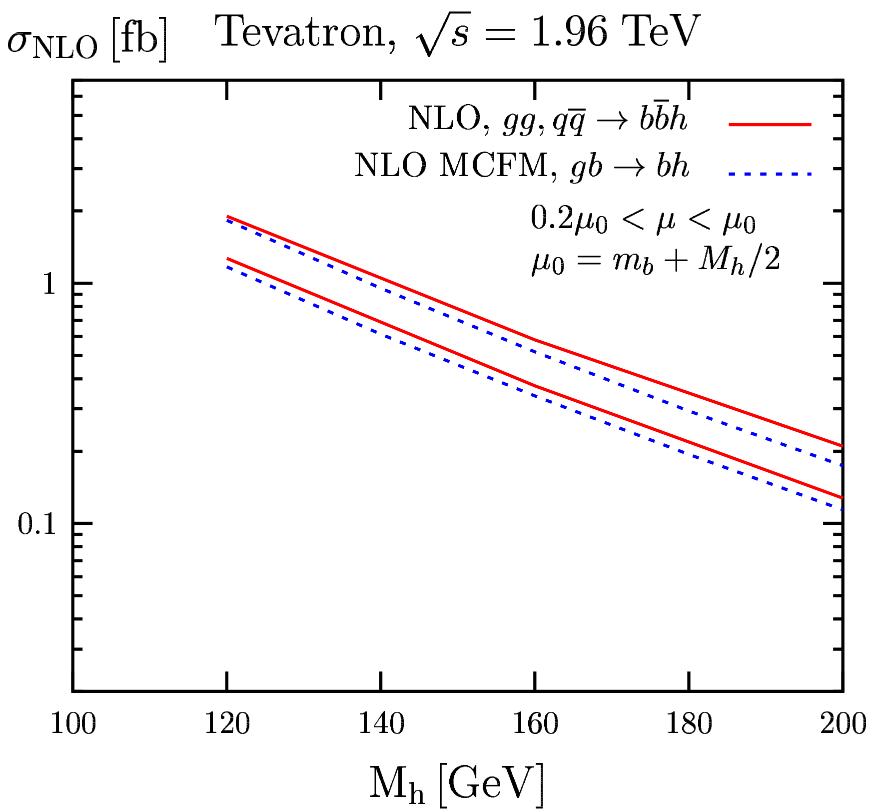


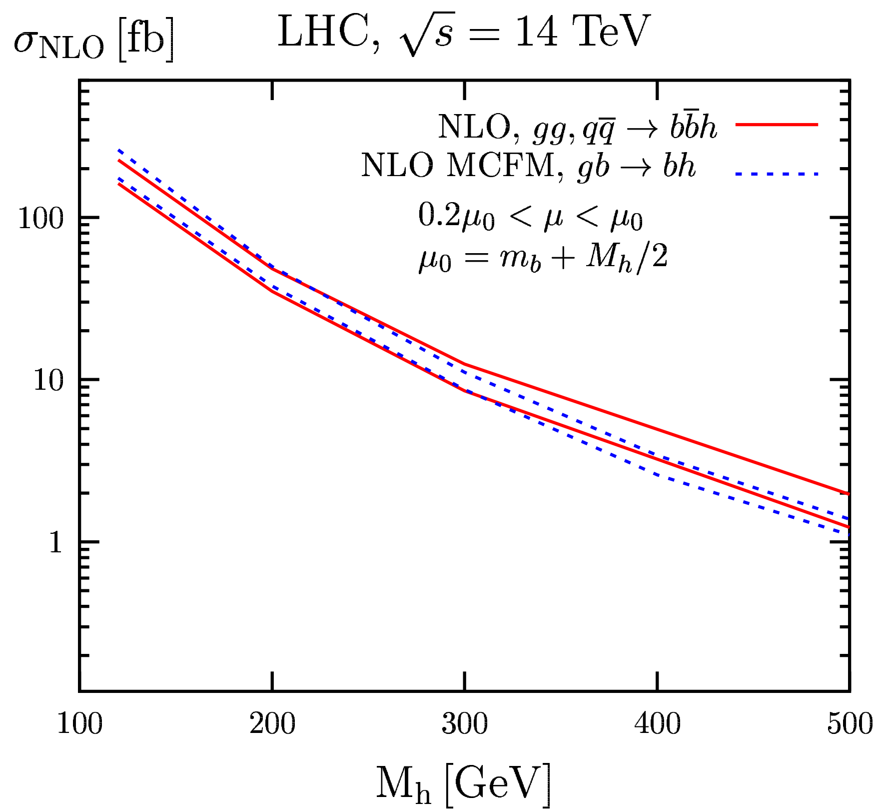
from S.Dawson, C.Jackson, L.Reina, D.W., in prep.

see also S.Dittmaier *et al.*, PRD 70 (2004), and J.Campbell *et al.* in LesHouches 2003 proceedings, hep-ph/0405302

M_h dependence – 1 b tagged

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





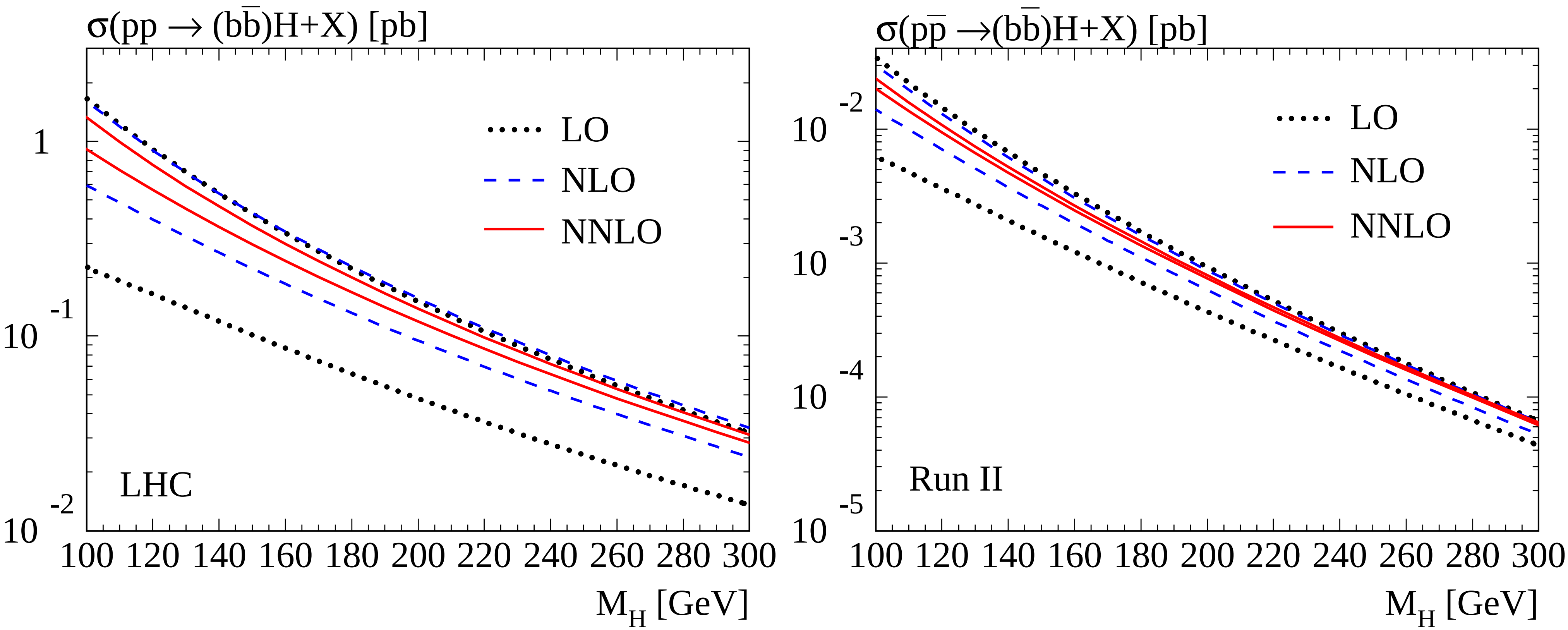
$gg, q\bar{q} \to b\bar{b}h$: from S.Dawson, C.Jackson, L.Reina, D.W., hep-ph/0408077, see also S.Dittmaier *et al.*, PRD 70 (2004)

$gb(\bar{b}) \to b(\bar{b})h$: from J.Campbell *et al.* in LesHouches 2003 procs. (hep-ph/0405302)

and closed top quark loop added to MCFM (J.Campbell *et al.*, PRD67 095002 (2003))

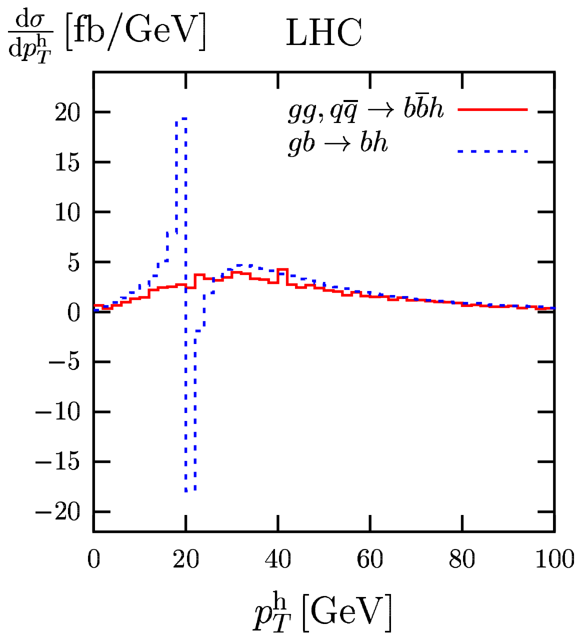
M_h dependence – 0 b tagged (VFS)

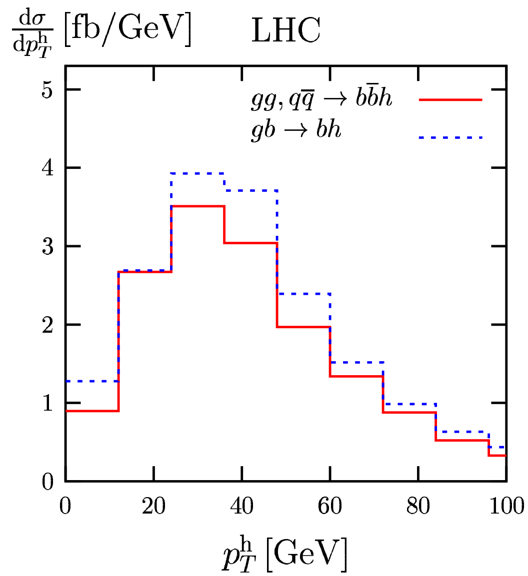
from R.Harlander, W.Kilgore, Phys.Rev. D68 (2003) 013001

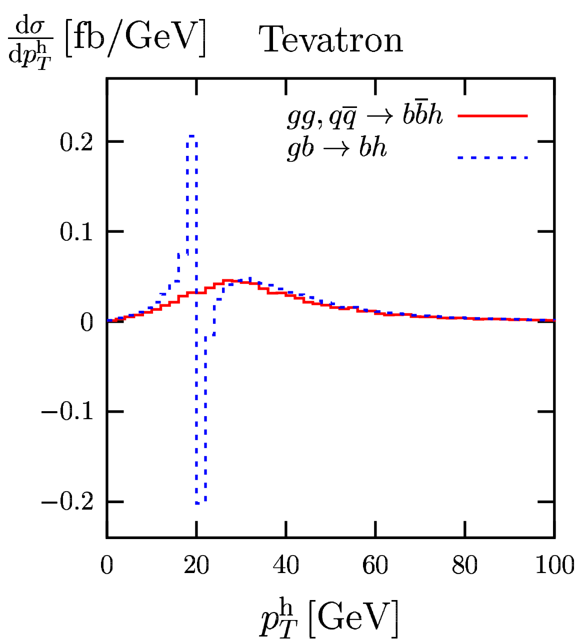


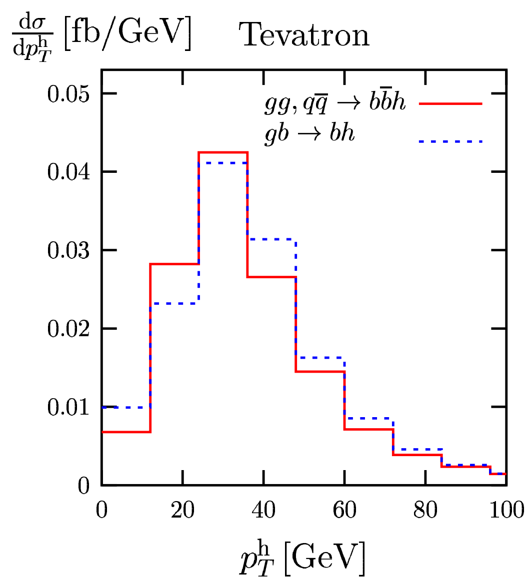
$\mu_F = (0.1, 0.7)M_h, \mu_R = M_h$

Effect of NLO QCD corrections on the Higgs p_T distribution:



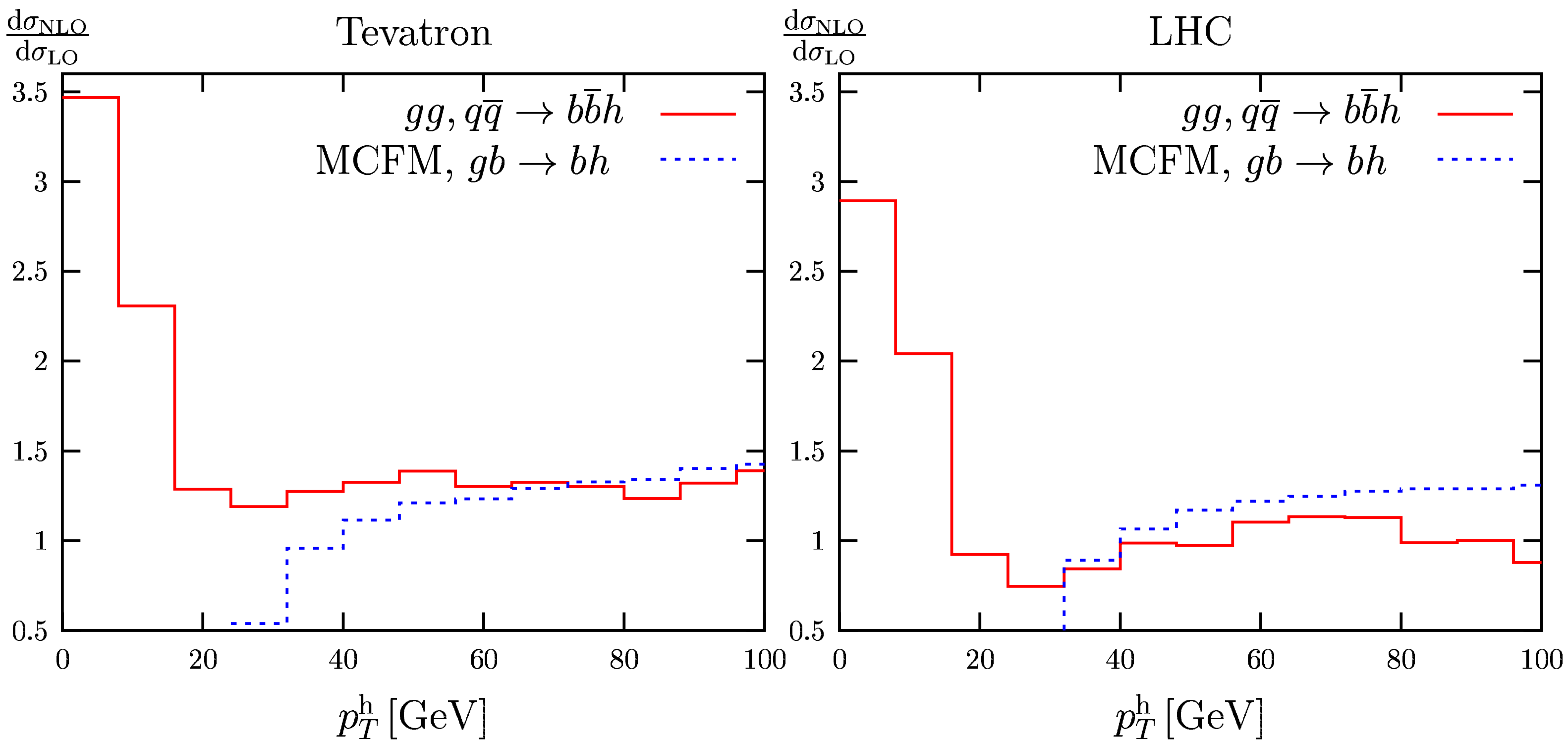






from S.Dawson, C.Jackson, L.Reina, D.W., hep-ph/0408077

Effect of NLO QCD corrections on the Higgs p_T distribution:



from S.Dawson, C.Jackson, L.Reina, D.W., hep-ph/0408077

Summary

- Higgs production in association with b quarks 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, hep-ph/0405302):

  $\rightarrow$ 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:

    $\rightarrow$ Results have been obtained for the inclusive, semi-inclusive and exclusive case. They are in good numerical agreement.

$\rightarrow$ 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 (5FNS).

  $\rightarrow$ The two NLO calculations, based on $gg, q\bar{q} \rightarrow b\bar{b}h$ (4FNS) and $gb(\bar{b}) \rightarrow b(\bar{b})h$ (5FNS) 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 (5FNS).

  $\rightarrow$ The predictions based on $gg, q\bar{q} \rightarrow b\bar{b}h$ (4FNS) and $b\bar{b} \rightarrow h$ (5FNS) subprocesses agree reasonably well within their respective theoretical uncertainties.

Possible improvements and outlook:

- 4FNS: Identification and resummation of large logarithms, $\ln(M_h/m_b)$, arising when integrating over the b quark p_T.
- Estimate of theoretical uncertainty on cross sections to Higgs production in association with b quarks due to PDF uncertainties.

  see, e.g, talk by Chris Jackson at this workshop