NLO QCD Predictions for Hadronic Higgs Production with Heavy Quarks

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1. The Search for the Higgs boson

The Higgs boson – a direct consequence of W and Z boson mass generation in the Standard Model (SM) via spontaneous symmetry breaking of the $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ gauge group. Goldstone (1961); Goldstone, Salam and Weinberg (1962); Higgs (1964,1966); Kibble (1967); Brout and Englert (1964); Guralnik, Hagen and Kibble (1964)

The Higgs particle so far eluded direct observation.

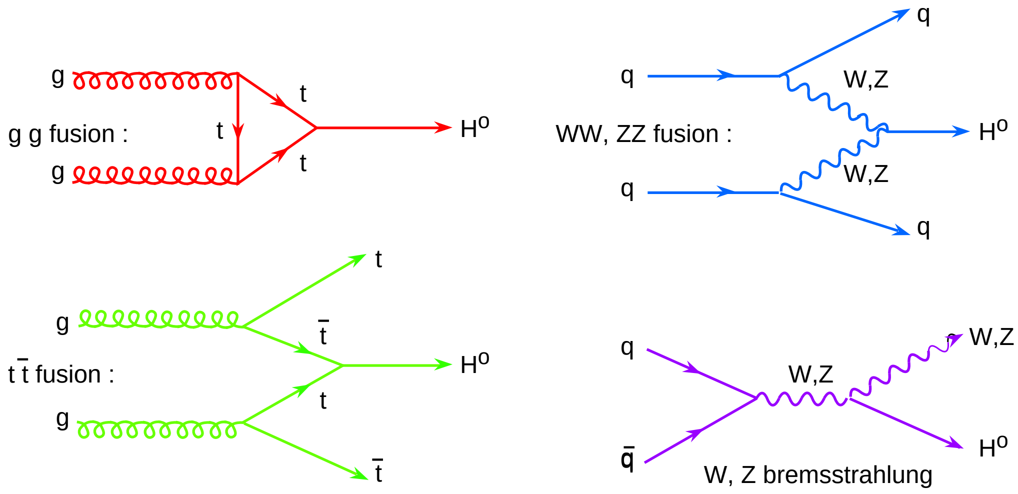
We know from direct (LEP2) and indirect searches (EWK fits) that the SM Higgs boson mass lies in the range

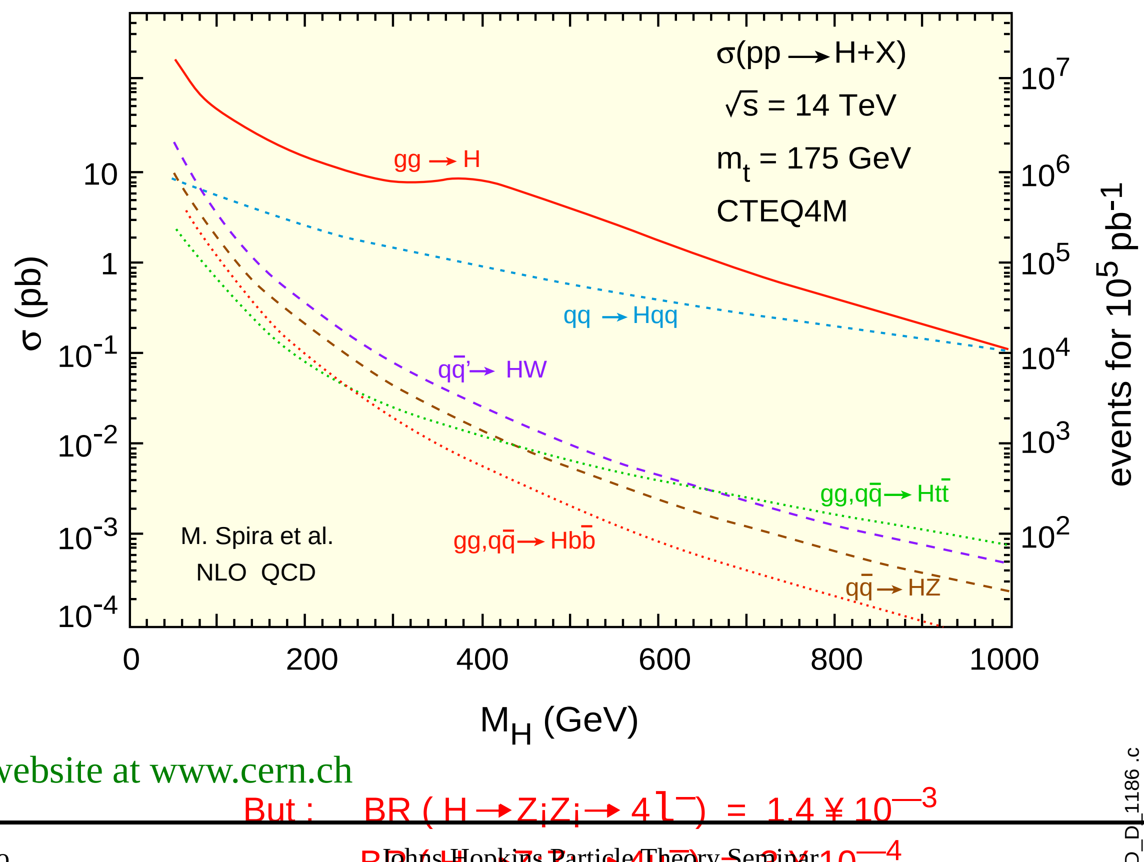
CERN-EP/2003-011, CERN-EP/2003-02 (update: LEPEWWG webpage)

$$114.4\,\mathrm{GeV} < M_H \lesssim 260\,\mathrm{GeV}\ (95\ \%\ \mathrm{C.L.})$$

Both $t\bar{t}h$ and $b\bar{b}h$ production processes will play an important role in Higgs discovery (SM (LHC) and MSSM (LHC and Tevatron)) and in the measurements of Higgs properties, e.g., of the top quark Yukawa coupling at the LHC.

H^o production at hadron colliders:





from the CMS website at www.cern.ch

But : BR (H → Z¡Z¡ → 4l⁻) = 1.4 ¥ 10^{-3}

BR (H → Z¡Z¡ → 4µ⁻) = 3 ¥ 10^{-4}

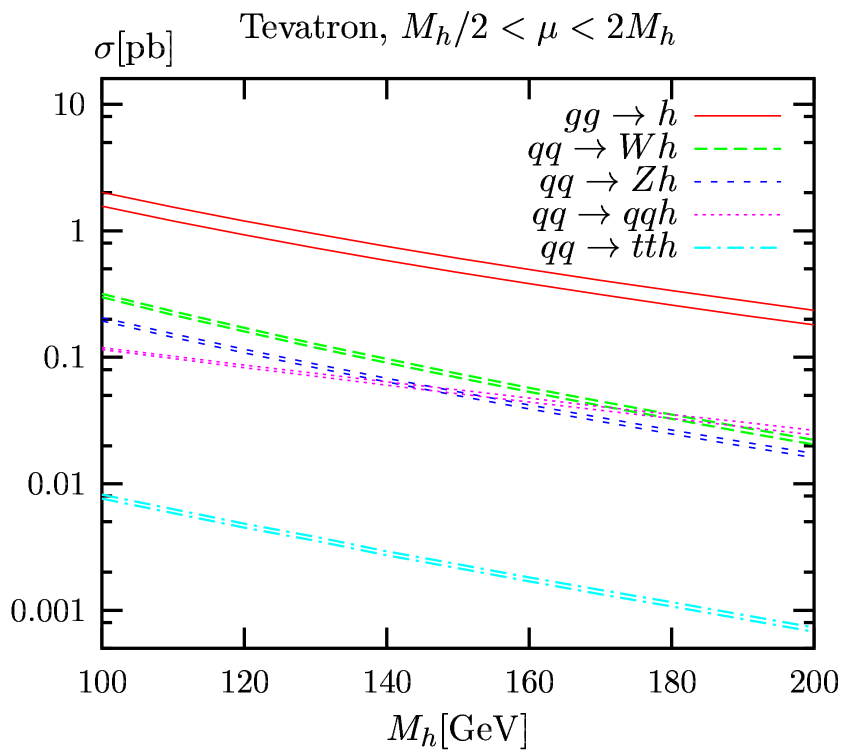
Dominant production modes: $gg \to H$ (background very large); $q\bar{q} \to WH, ZH$ (most promising for leptonic decay of W/Z)

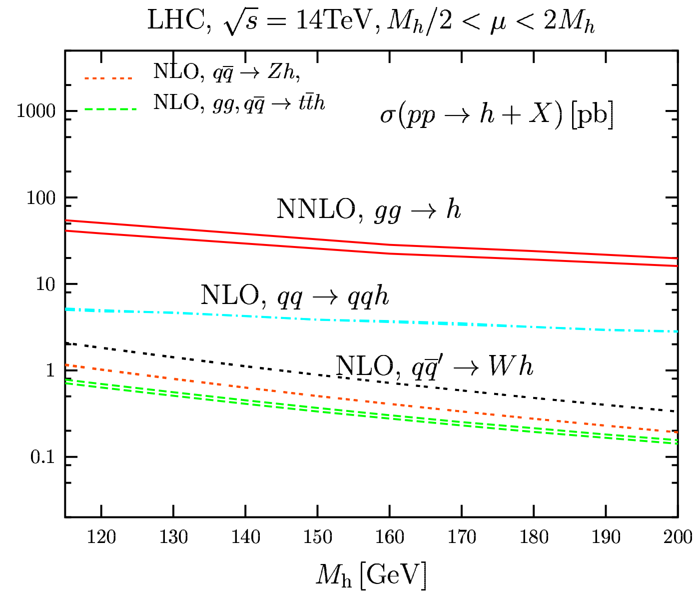
State-of-the-art of QCD predictions for Higgs processes at hadron colliders:

production process	$\sigma_{\mathrm{NLO,NNLO}}$ by
$gg \to H$	S.Dawson, NPB 359 (1991); A.Djouadi, M.Spira, P.Zerwas, PLB 264 (1991)
	C.J.Glosser, C.R.Schmidt, JHEP (2002); V.Ravindran *et al*,NPB 634 (2002);
	D. de Florian *et al.*, PRL 82 (1999) (distrib.)
	V.Ravindran *et al*, NPB 665 (2003) (NNLO)
	R.Harlander, W.Kilgore, PRL 88 (2002) (NNL0)
	C.Anastasiou, K.Melnikov, NPB 646 (2002) (NNL0)
$q\bar{q} \to (W,Z)H$	T.Han, S.Willenbrock, PLB 273 (1991)
$q\bar{q} \to q\bar{q}H$	T.Han, G.Valencia, S.Willenbrock, PRL 69 (1992)
	T.Figy, C.Oleari, D.Zeppenfeld, PRD 68 (2003) (distrib.)
$gg, q\bar{q} \to t\bar{t}H$	W.Beenakker *et al.*, PRL 87 (2001), NPB 653 (2003)
	S.Dawson *et al.*, PRL 87 (2001), PRD 65 (2002), PRD 68 (2003)
$gg, q\bar{q} \to b\bar{b}H$	S.Dittmaier, M.Kramer, M.Spira, hep-ph/0309204 (2003)
	S.Dawson *et al.*, PRD 69 (2004)
$gb(\bar{b}) \to b(\bar{b})H$	for a review see J.Campbell *et al.*, Les Houches 2003 procs., hep-ph/0405302
$b\bar{b} \to H$	for a review see J.Campbell *et al.*, Les Houches 2003 procs., hep-ph/0405302
	R.Harlander, W.Kilgore, PRD 68 (2003) (NNL0)

$\sigma_{NLO,NNLO}$ for Higgs production processes at hadron colliders:

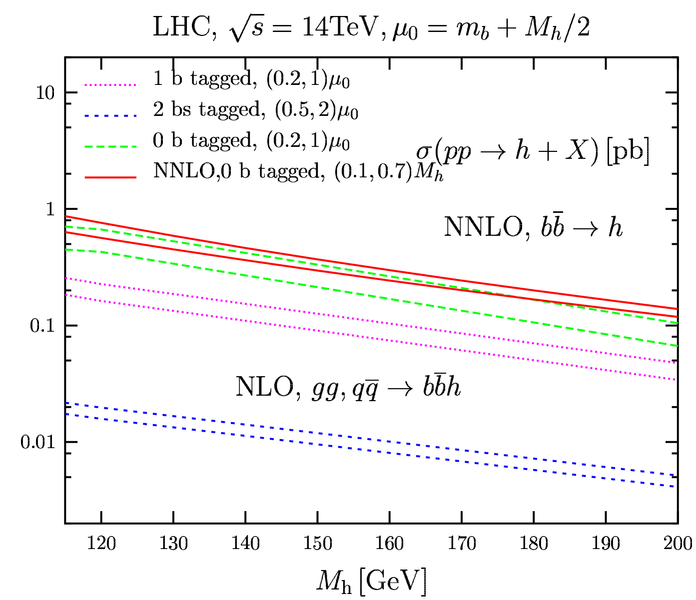
(for references see previous slide)





from S.Dawson *et al.*, hep-ph/0210109

$t\bar{t}h$: μ varied between $\mu_0 = m_t + M_h/2$ and $2\mu_0$.



from S.Dawson *et al.*, in prep. (prelim.)

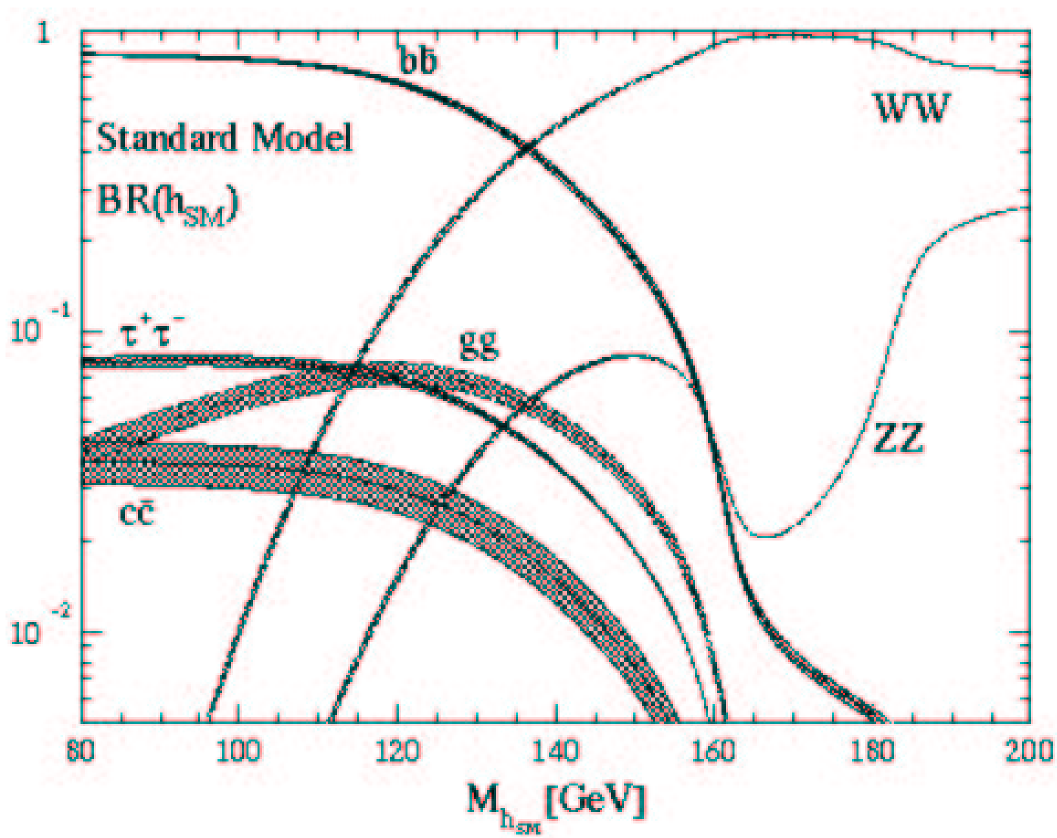
Many thanks to W.Kilgore and R.Harlander for providing their NNLO results.

Dominant decay modes:

M_H <135 GeV: $H \to b\bar{b}$ with $BR = 43\%$,

M_H >135 GeV: $H \to W^+W^-$ with $BR = 40\%$

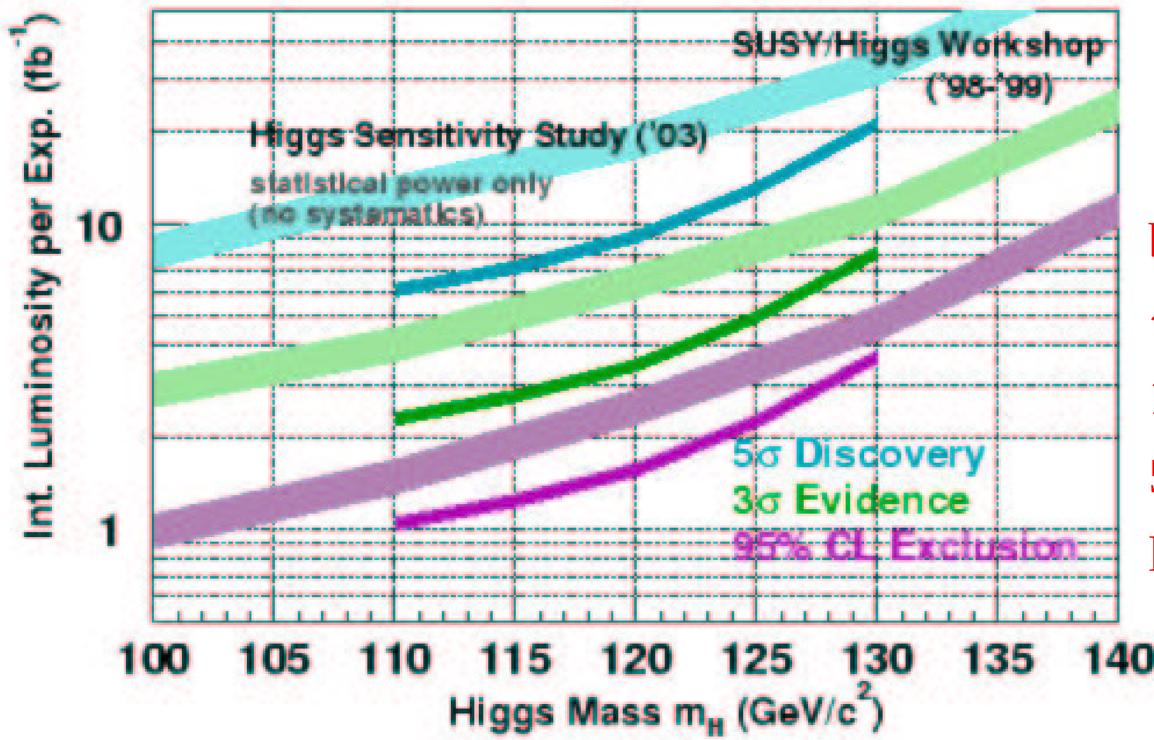
Branching ratios of the dominant SM Higgs decay modes (including QCD corrections):



from M.Carena and H.Haber, hep-ph/0208209
HDECAY (A.Djouadi *et al.*)
M.Spira, hep-ph/9810289

Tevatron SM Higgs discovery potential

Integrated luminosity per experiment for a 95% CL exclusion of a SM Higgs or a 3σ or a 5σ discovery:



Tevatron Higgs Sensitivity Study
FERMILAB-PUB-03/320E

based on Z/WH production only, $Z/W \to ll, l\nu, H \to b\bar{b}$

10% syst. uncertainty in S/B results in a 5,15,20 % increase in $95\% CL, 3\sigma, 5\sigma$ luminosity thresholds ($M_H = 120$ GeV)

Can $t\bar{t}H$ help ?

SM Higgs discovery reach at the Tevatron Run II:

$M_H \lesssim 125$ GeV (95 % C.L. with 2 fb^{-1}, 3 σ evidence with 5 fb^{-1})

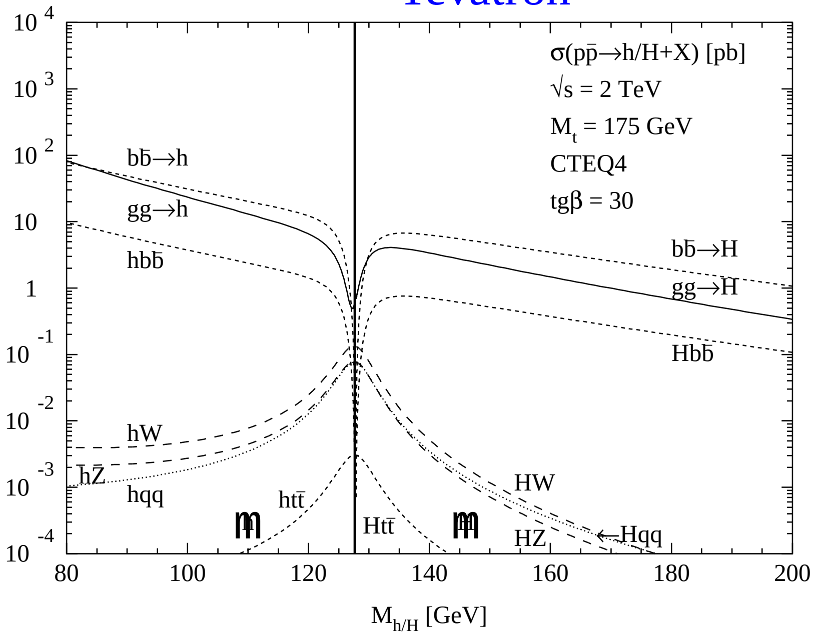
$M_H = 130$ GeV can be excluded with 4 fb^{-1}

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

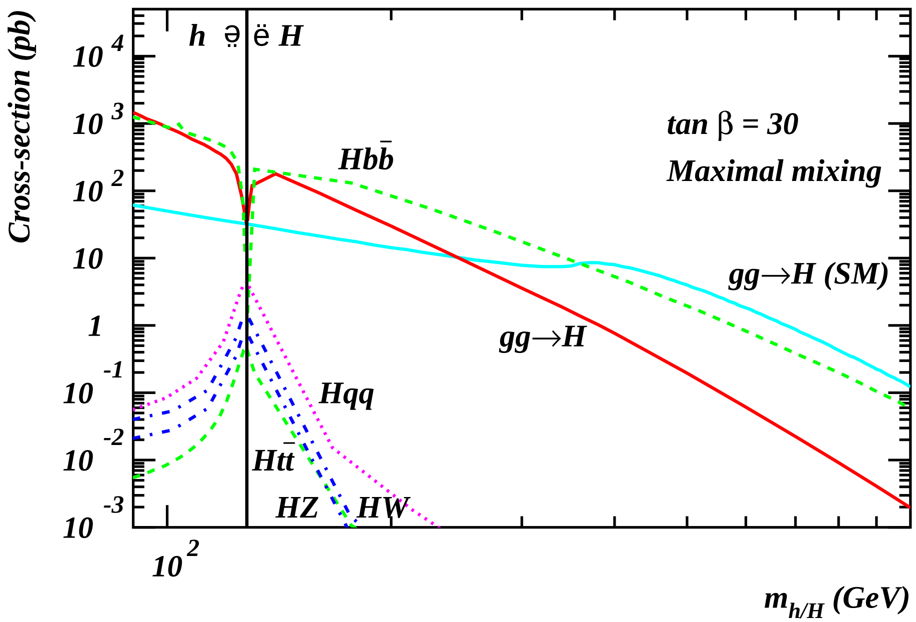
In the MSSM, however, the cross sections to $p\bar{p}, pp \to b\bar{b}h, h = h^0, H^0, A^0$, are enhanced with respect to the SM for large values of $\tan\beta$:

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

Tevatron



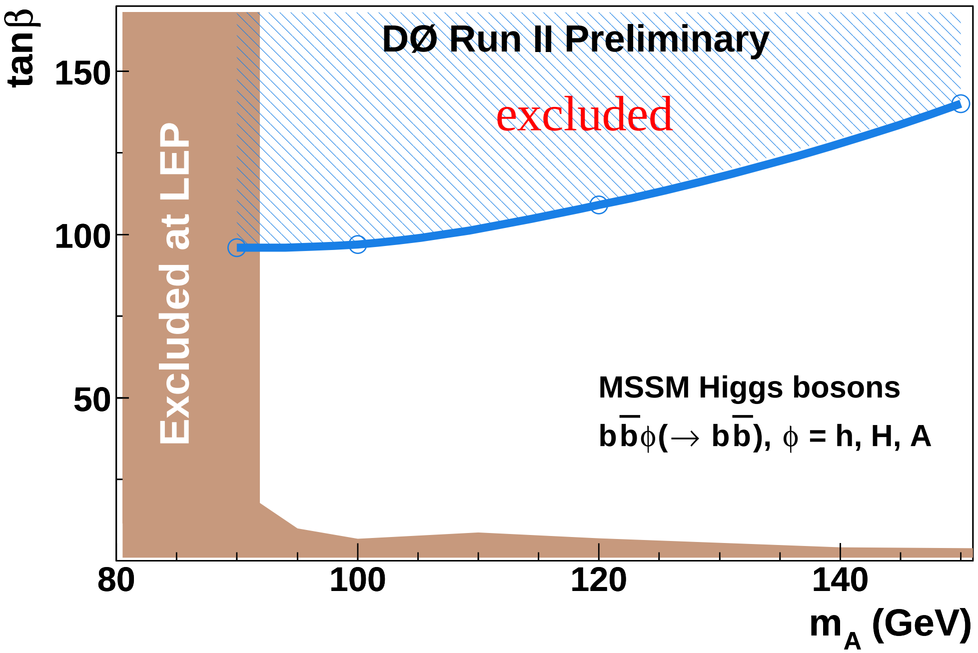
LHC

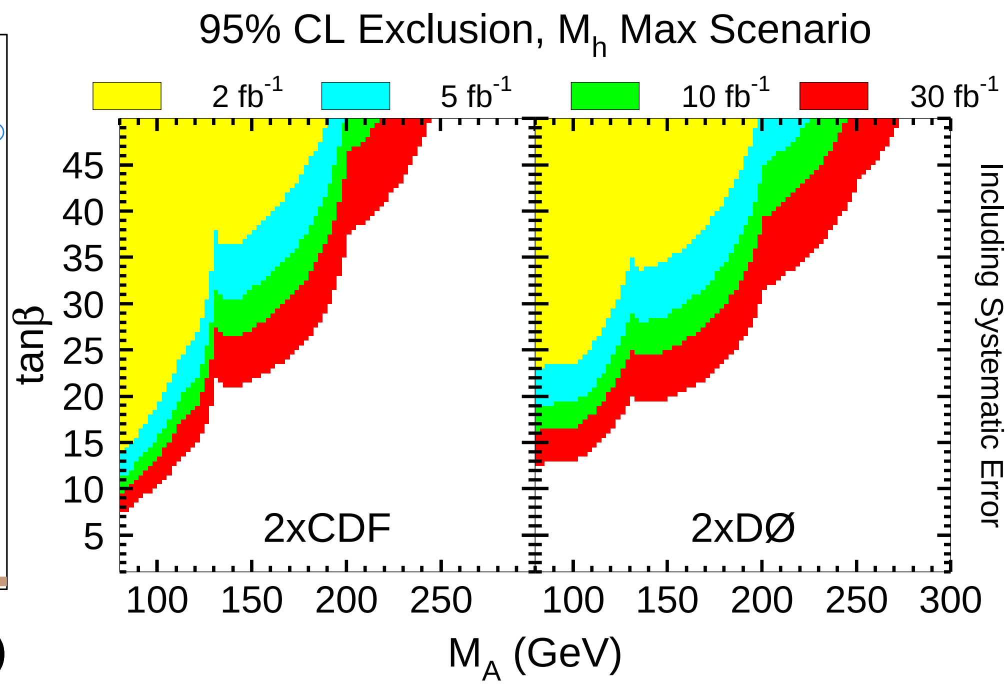


from M.Carena, H.Haber, Prog.Part.Nucl.Phys.50 (2003)

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

Search for MSSM $h = H^0, h^0, A^0$ 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):





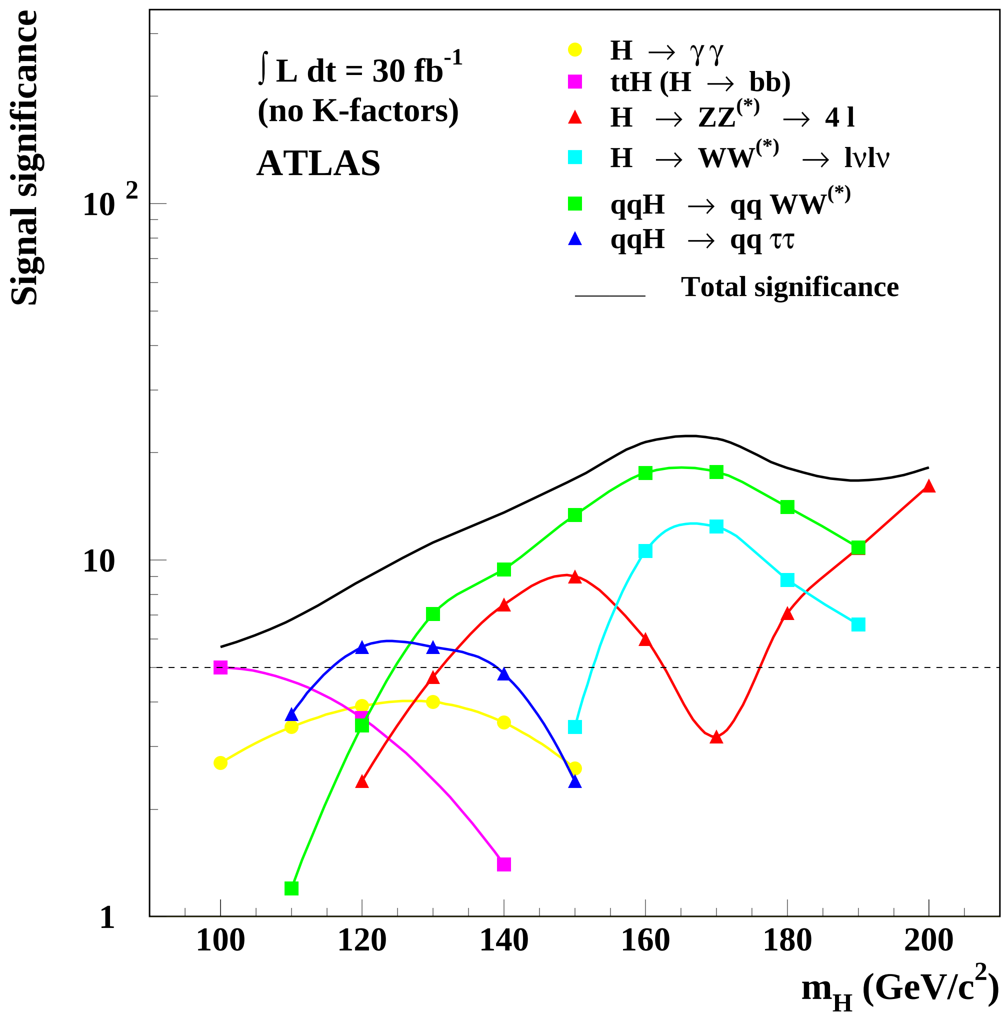
from The D0 collaboration, D0 Note 4366 - CONF

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

see also talk by A.Melnitchouk, Pheno 2004

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

LHC SM Higgs discovery potential

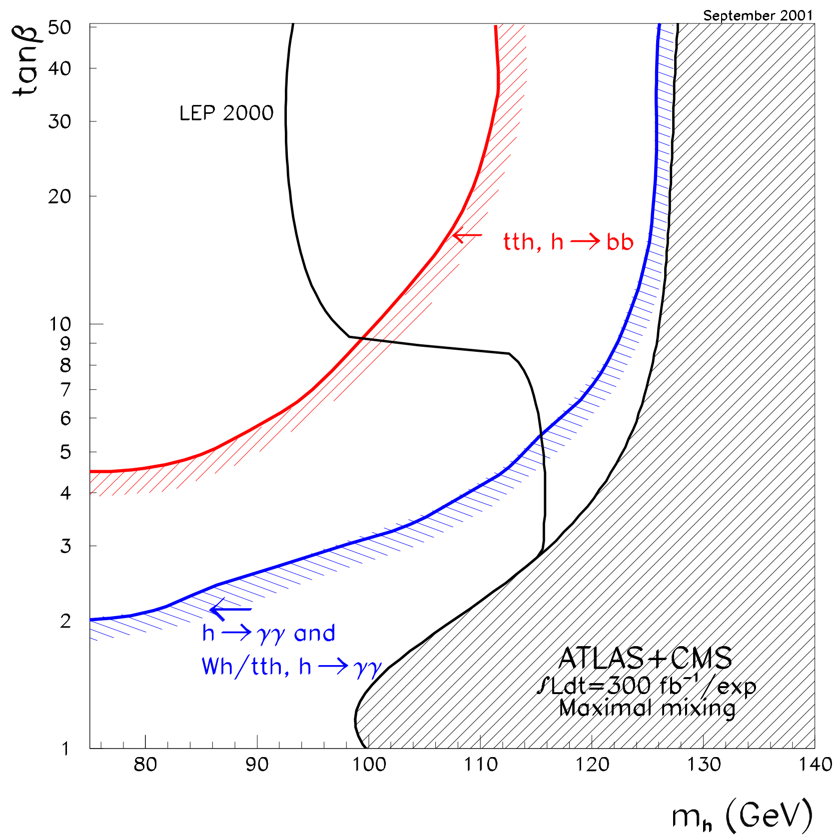


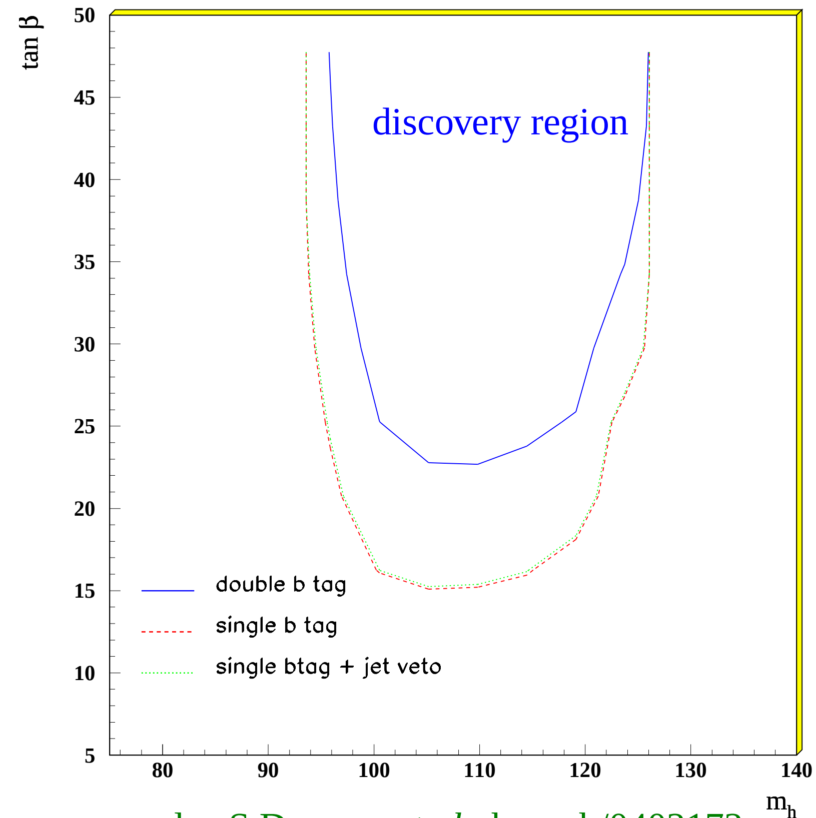
from S.Gentile
ATL-PHYS-2004-009 (and references therein)

For $M_H < 130$ GeV the SM Higgs search is mainly through $t\bar{t}H$.

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

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

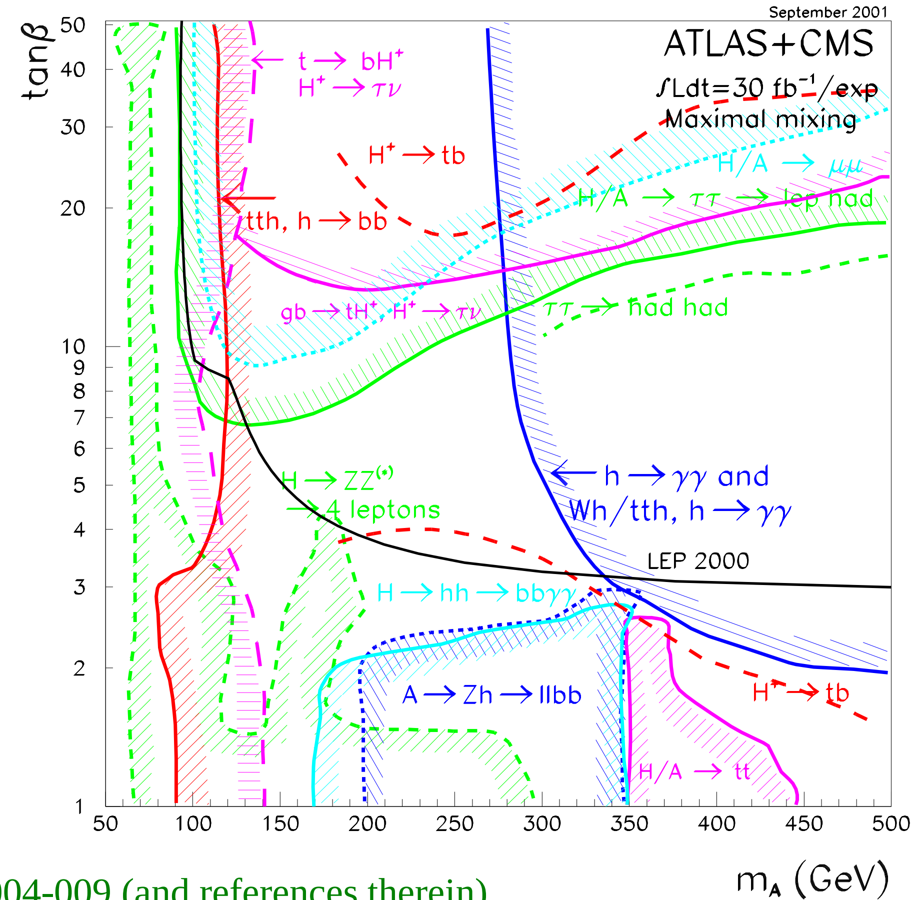




see also S.Dawson *et al.*, hep-ph/0402172

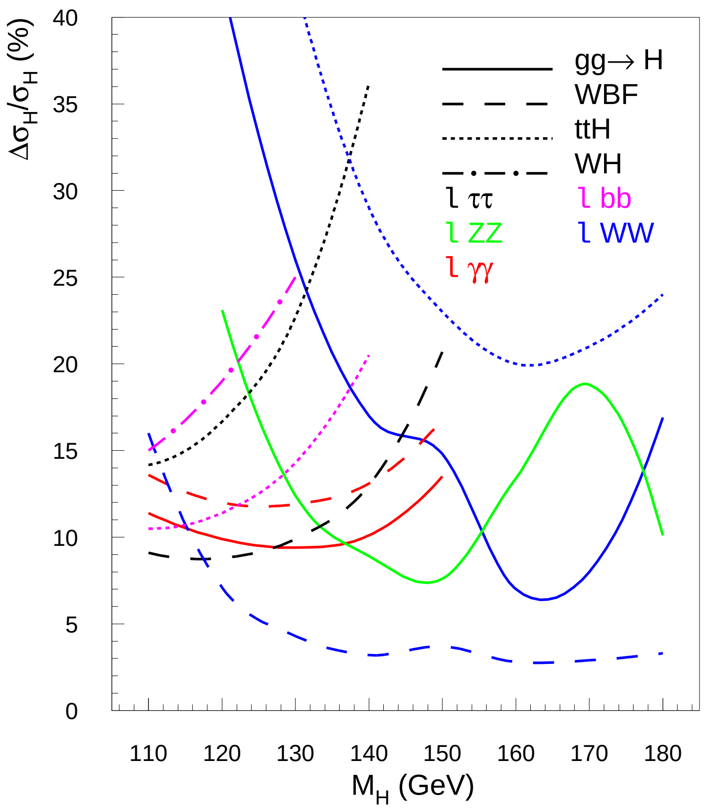
from S.Gentile, ATL-PHYS-2004-009 (and references therein)

The LHC sensitivity for MSSM Higgs boson discoveries (5σ curves):



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

Expected relative error on the determination of $\sigma_{\rm Higgs}$ at the LHC:



from A.Belyaev and L.Reina, JHEP 0208 (2002)

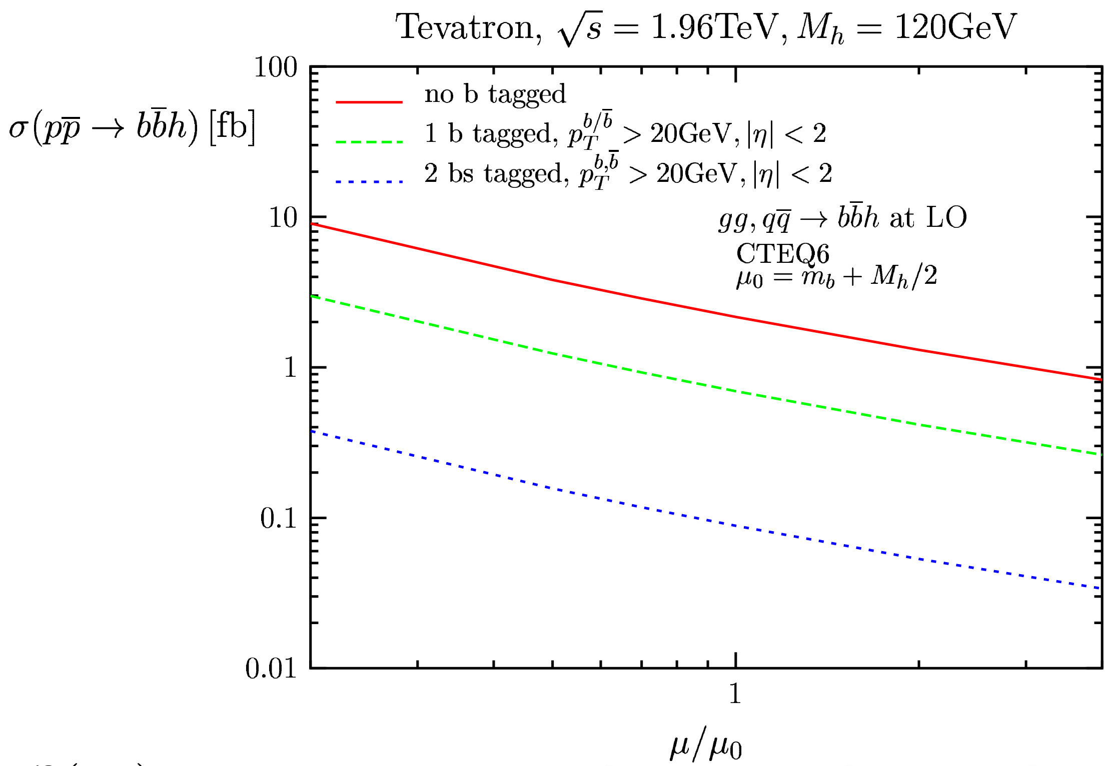
see also review by D.Zeppenfeld, hep-ph/0203123
Based on studies by ATLAS, CMS, A.Belyaev, N.Kaur, F.Maltoni, T.Plehn, D.Rainwater, L.Reina, S.Willenbrock, D.Zeppenfeld

$t\bar{t}h$ directly probes the top quark Yukawa coupling:
at the LHC with 200 fb^{-1} and $M_H \lesssim 130$ GeV g_{ttH} can be measured with a precision of 15-20 %.

from D.Zeppenfeld, hep-ph/0203123 (and references therein)

Need for NLO QCD calculations

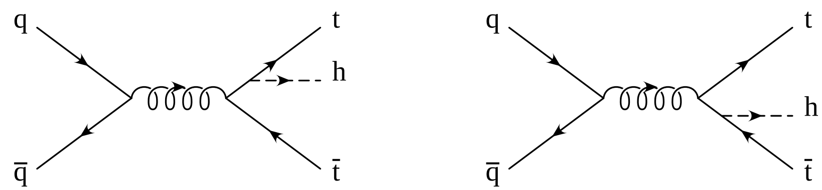
- LO calculations have very strong renormalization/factorization scale dependence:



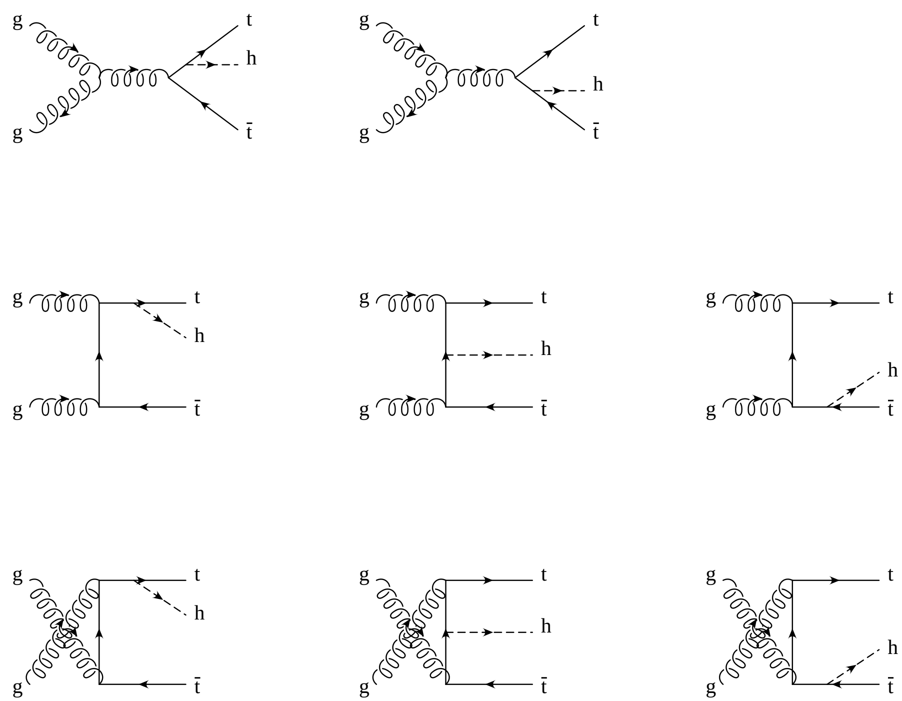
- $\mathcal{O}(\alpha_s)$ corrections can strongly increase/decrease the total production rate.
- $\mathcal{O}(\alpha_s)$ corrections may affect the shape of distributions.

2. Associated $t\bar{t}$ Higgs production at hadron colliders

$t\bar{t}H$ production at the Tevatron $p\bar{p}$ collider is dominated by the $q\bar{q}$ initiated process ($> 95\%$ of $\sigma_{\rm LO}$ at 2 TeV):



$t\bar{t}H$ production at the LHC pp collider is dominated by the gg initiated process (but all other production processes should be taken into account too):



$O(\alpha_s)$ corrections to $p\bar{p}, pp \to t\bar{t}H$ production: Some technical details

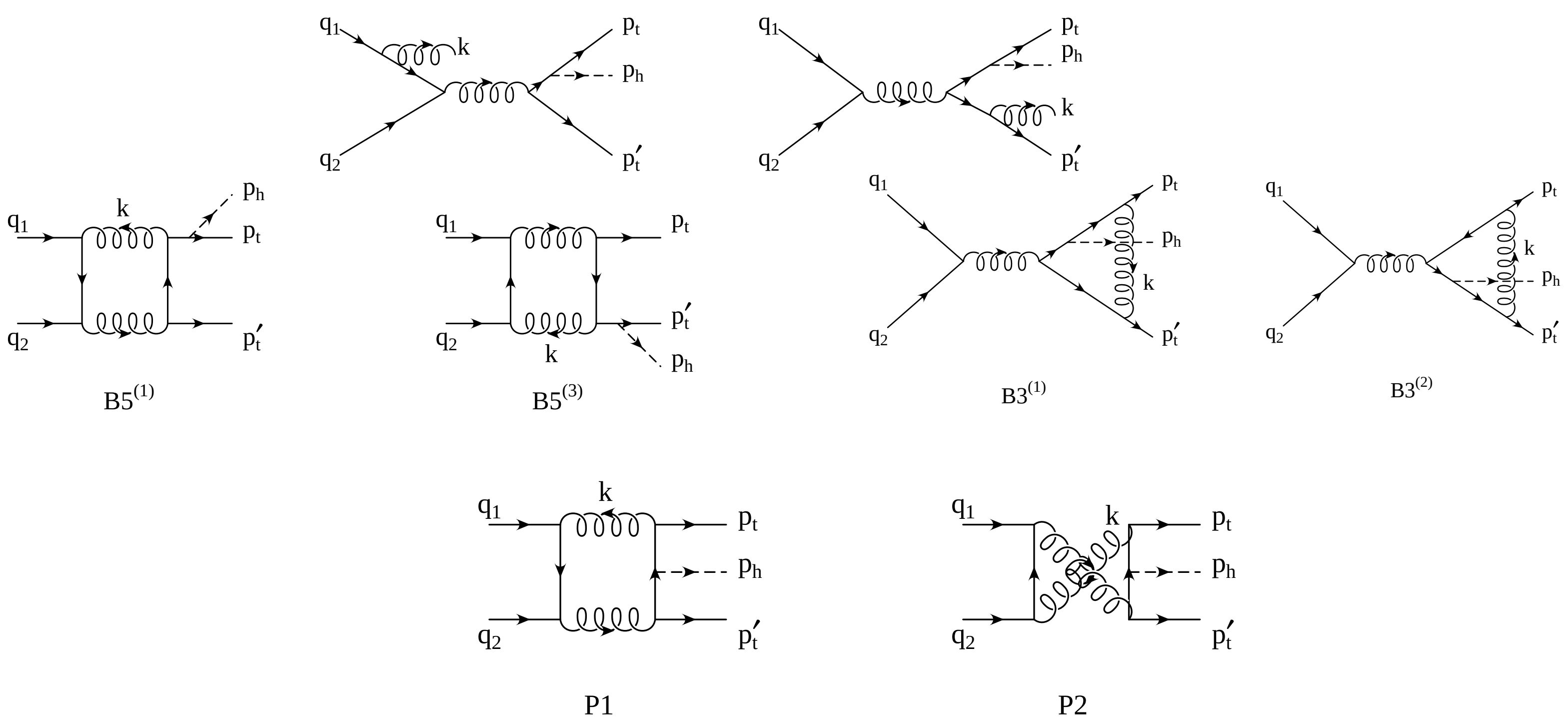
W.Beenakker, S.Dittmaier, M.Krämer, B.Plümber, M.Spira, P.M.Zerwas, PRL 87 (2001), NPB 653 (2003)

L.Reina, S.Dawson, PRL 87 (2001), L.Reina, S.Dawson, DW, PRD 65 (2002)

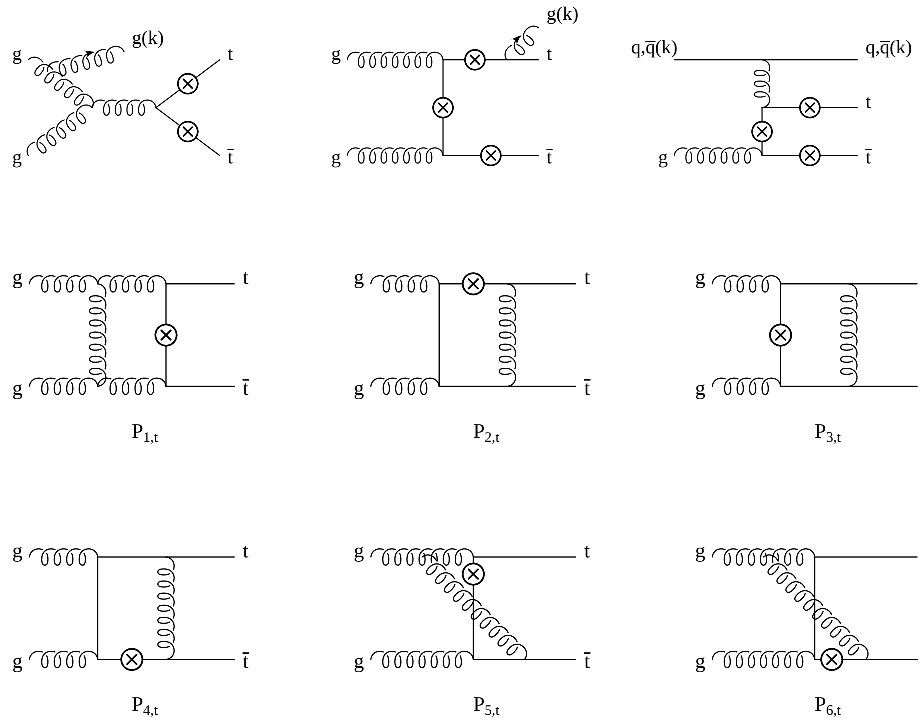
S.Dawson, L.H.Orr, L.Reina, DW, PRD 67 (2003)

At NLO QCD the cross section includes virtual and real gluon radiation:

Examples of real and virtual $\mathcal{O}(\alpha_s)$ corrections to $p\bar{p} \to t\bar{t}H$



Examples of real and virtual $\mathcal{O}(\alpha_s)$ corrections to $pp \to t\bar{t}H$



The calculations of the $\mathcal{O}(\alpha_s)$ corrections to $gg \to t\bar{t}H$ and $q\bar{q} \to t\bar{t}H$ are technically similar.

However, in the case of $gg \to t\bar{t}H$ there are new challenges, e.g., spurious singularities arising in the reduction of pentagon tensor integrals.

NLO QCD total inclusive cross section to $p\bar{p}, pp \to t\bar{t}H$:

$$\sigma_{NLO} = \sum_{ij=q\bar{q},gg,qg} \frac{1}{1+\delta_{ij}} \int dx_1 dx_2 [\mathcal{F}_i^p(x_1,\mu)\mathcal{F}_j^{\bar{p}}(x_2,\mu)\hat{\sigma}^{ij}_{\rm NLO}(x_1,x_2,\mu) + (1 \leftrightarrow 2)]$$

with the parton level cross sections

$$\hat{\sigma}^{ij}_{\rm NLO} = \hat{\sigma}^{ij}_{\rm LO} + \frac{\alpha_s}{4\pi}\delta\hat{\sigma}^{ij}_{\rm NLO} \text{ with } \delta\hat{\sigma}^{ij}_{\rm NLO} = \hat{\sigma}^{ij}_{\rm virt} + \hat{\sigma}^{ij}_{\rm real}$$

$\hat{\sigma}^{ij}_{\rm virt}$:

- UV divergences: renormalized in $d = 4 - 2\epsilon$ dimensions by suitable set of counterterms (modified $\overline{MS}$ scheme, on-shell subtraction for top)
- IR divergences: regularized in $d = 4 - 2\epsilon$ dimensions $\Rightarrow$ soft and collinear singularities appear as poles in $\frac{1}{\epsilon^2}, \frac{1}{\epsilon}$. IR singularities are completely canceled by corresponding IR poles in

$\hat{\sigma}^{ij}_{\rm real}$:

- IR divergences: extracted by suitable cuts on gluon phase space (phase space slicing): two and one cut-off PSS method using crossing symmetry and color ordered amplitudes. Remaining initial-state IR singularities are absorbed in PDFs (mass factorization).

$$\hat{\sigma}^{ij}_{\text{real}} = \int d(PS_4)|\mathcal{A}_{real}(ij \to t\bar{t}H + g)|^2$$

Phase Space Slicing: isolate the region of the $t\bar{t}H + g$ phase space where

$$s_{ig} = 2p_i \cdot p_g = 2E_i E_g (1 - \beta_i \cos\theta_{ig}) \to 0$$

by introducing suitable cutoff parameters.

two cut-off PSS method: δ_s, δ_c

e.g. Bergman, Baer, Ohnemus, Owens, Reno, ..., for a review see B.Harris, J.Owens, PRD 65 (2002)

$$E_g < \delta_s \sqrt{s}/2 \;\; ; \;\; (1 - \cos\theta_{ig}) < \delta_c$$

one cut-off PSS method: s_{min}

Giele, Glover, and Kosower; Keller and Laenen

$$s_{ig} < s_{min}$$

and compute $\hat{\sigma}^{ij}_{real}$

- analytically below the cut-off(s)

Together with $\hat{\sigma}^{ij}_{\text{virt}}$ this constitutes the weight with $2 \to 3$ kinematics.

- numerically above the cut-off(s) $\Rightarrow$ weight with $2 \to 4$ kinematics.

Phase Space Slicing with two cut-offs

e.g. Bergman, Baer, Ohnemus, Owens, Reno, ..., for a review see B.Harris, J.Owens, PRD 65 (2002)

$$\hat{\sigma}^{ij}_{real}(ij \to t\bar{t}H + g) = \hat{\sigma}_{soft}(E_g < \frac{\sqrt{s}}{2}\delta_s) + \hat{\sigma}_{hard}(E_g > \frac{\sqrt{s}}{2}\delta_s)$$

In the soft limit ($E_g \to 0$):

$$d(PS_4) \xrightarrow{soft} d(PS_3)d(PS_g) = d(PS_3)\frac{d^{d-1}k}{(2\pi)^{d-1}2E_g}$$

$$|\mathcal{A}_{real}(ij \to t\bar{t}h + g)|^2 \xrightarrow{soft} (4\pi\alpha_s)|\mathcal{A}_{LO}|^2\Phi_{eik}$$

where the eikonal factor Φ_{eik} contains the soft poles

$$\Phi_{eik} \propto \sum_{ij}\left(\frac{s_{ij}}{s_{ig}s_{jg}} - \frac{m_i^2}{s_{ig}^2} - \frac{m_j^2}{s_{jg}^2}\right)$$

$$\hat{\sigma}_{soft} = \int d(PS_3)|A_{LO}|^2\int d(PS_g)\Phi_{eik}$$

Analytical integration in $d = 4 - 2\epsilon$ dimensions yields IR divergences as poles in $\epsilon \to 0$: $\hat{\sigma}_{soft} \propto \frac{1}{\epsilon}, \frac{1}{\epsilon^2}$

. . . moreover

$$\hat{\sigma}_{hard} = \hat{\sigma}_{coll}((1-\cos\theta_{ig}) < \delta_c) + \hat{\sigma}_{non-coll}((1-\cos\theta_{ig}) > \delta_c)$$

In the collinear limit ($i \to i'g$, $p'_i = z p_i$, $p_g = (1-z)p_i$)

$$d(PS_4)(ij \to t\bar{t}h + g) \stackrel{collinear}{\longrightarrow} d(PS_3)(i'j \to t\bar{t}h) z d(PS_g)$$

$$|\mathcal{A}_{real}(ij \to t\bar{t}h + g)|^2 \stackrel{collinear}{\longrightarrow} |A_{LO}|^2 (4\pi\alpha_s) \frac{2P_{ii'}(z)}{z\, s_{ig}}$$

($P_{ii'}$: AP-splitting function)

$$\hat{\sigma}_{coll} \propto \int d(PS_3)|A_{LO}|^2 \int d(PS_g) \sum_i \frac{P_{ii'}}{s_{ig}}$$

Analytical integration in $d = 4 - 2\epsilon$ dimensions yields collinear IR divergences as pole in $\epsilon \to 0$: $\hat{\sigma}_{coll} \propto \frac{1}{\epsilon}$

The remaining real hard part

$$\hat{\sigma}_{non-coll} = \int d(PS_4)_{non-coll} |\mathcal{A}_{real}(q\bar{q} \to t\bar{t}h + g)|^2$$

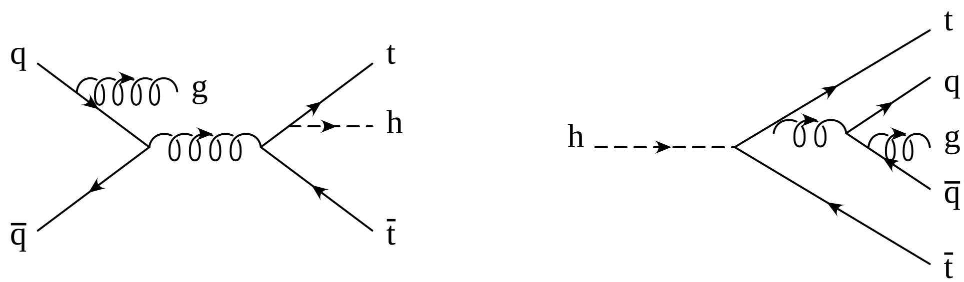
is computed numerically.

Phase Space Slicing with one cut-off

Giele, Glover, and Kosower; Keller and Laenen

- Cross all partons to final state:

$$q\bar{q} \to t\bar{t}h(+g) \quad \text{becomes} \quad h \to q\bar{q}t\bar{t}(+g) \quad \text{(same for gg initial state)}$$



- Reduce $\hat{\sigma}^{q\bar{q}t\bar{t}h}_{real}$ to color ordered amplitudes using

$$T^a_{c_1c_2}T^a_{c_3c_4} = \frac{1}{2}\left(\delta_{c_1c_4}\delta_{c_3c_2} - \frac{1}{N}\delta_{c_1c_2}\delta_{c_3c_4}\right)$$

so that

$$\mid \mathcal{A}_{real} \mid^2 \quad \propto \quad \left\{ \frac{N}{2}\left[|B_1|^2 + |B_2|^2\right] + \frac{1}{2N}\left[-2|B_3+B_4|^2 + |B_3|^2 + |B_4|^2\right] \right\}$$

- Introduce a cut-off parameter s_{min}; the radiated gluon is considered soft/collinear if $s_{ig} < s_{min}$.

  Use color ordered amplitudes to systematically factor out soft/collinear divergences.

- Cross $q\bar{q}$ to initial state, H to final state:
  - interchange q and $\bar{q}$ accordingly
  - add crossing function:

$$\hat{\sigma}^{q\bar{q}}_{real} = \hat{\sigma}_{soft} + \hat{\sigma}_{coll} + \hat{\sigma}_{crossing} + \hat{\sigma}_{non-coll}$$

Final steps

- Add virtual $\mathcal{O}(\alpha_s)$ corrections $\Rightarrow$ IR divergences in $\hat{\sigma}_{virtual}$ are canceled by corresponding divergences in $\hat{\sigma}_{soft} + \hat{\sigma}_{coll}(+\hat{\sigma}_{crossing})$.

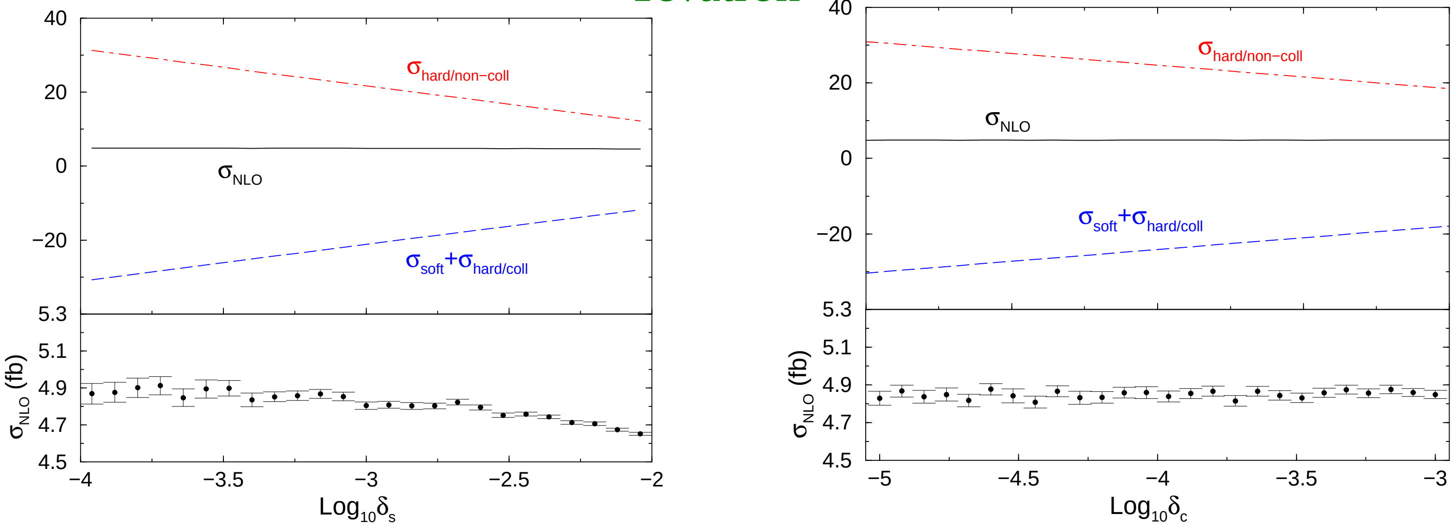
- Mass factorization

  When convoluting $\hat{\sigma}^{NLO}_{q\bar{q}}$ with the PDFs the remaining initial-state IR singularities are absorbed into the PDFs.

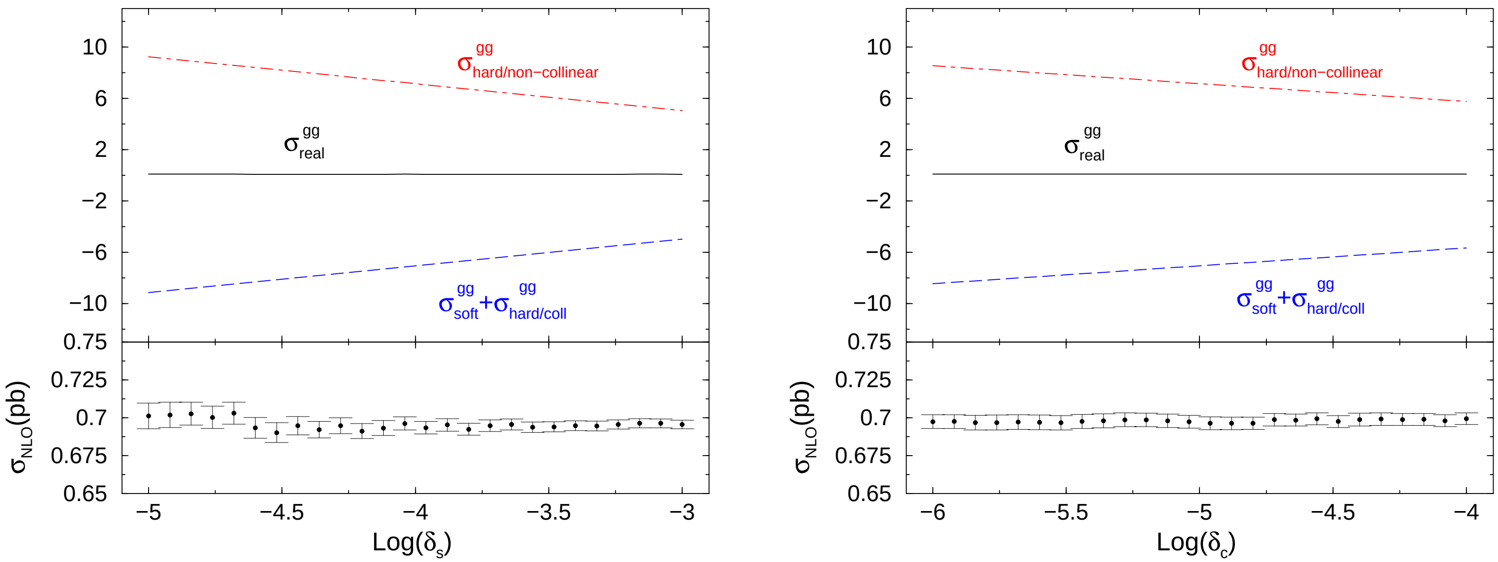
Cancellation of cut-off dependences in $\sigma_{\rm NLO}$

from L.Reina, S.Dawson, DW, PRD 65 (2002); S.Dawson, L.H.Orr, L.Reina, DW, PRD 67 (2003)

Tevatron

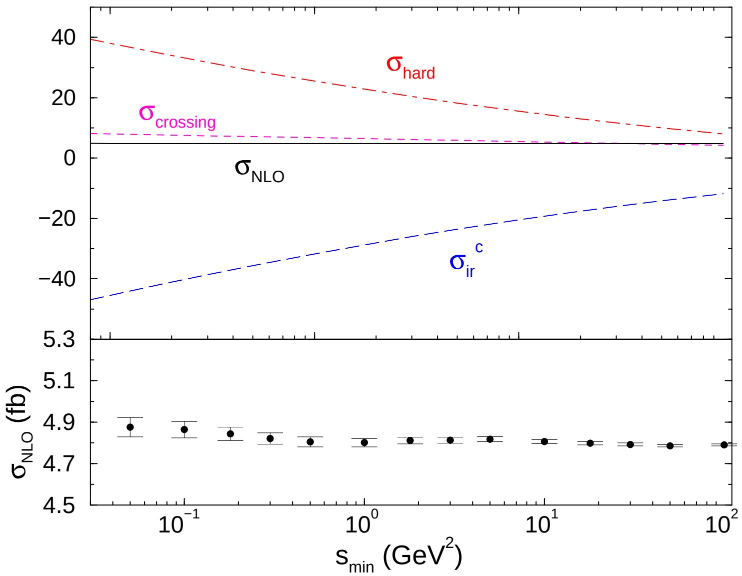


LHC

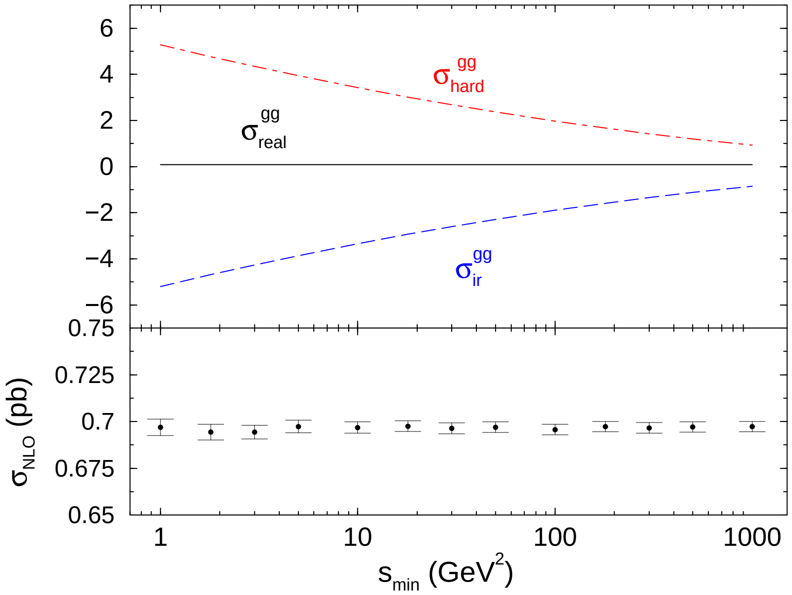


s_{min} dependence cancels in $\sigma_{\rm NLO}$

Tevatron



LHC

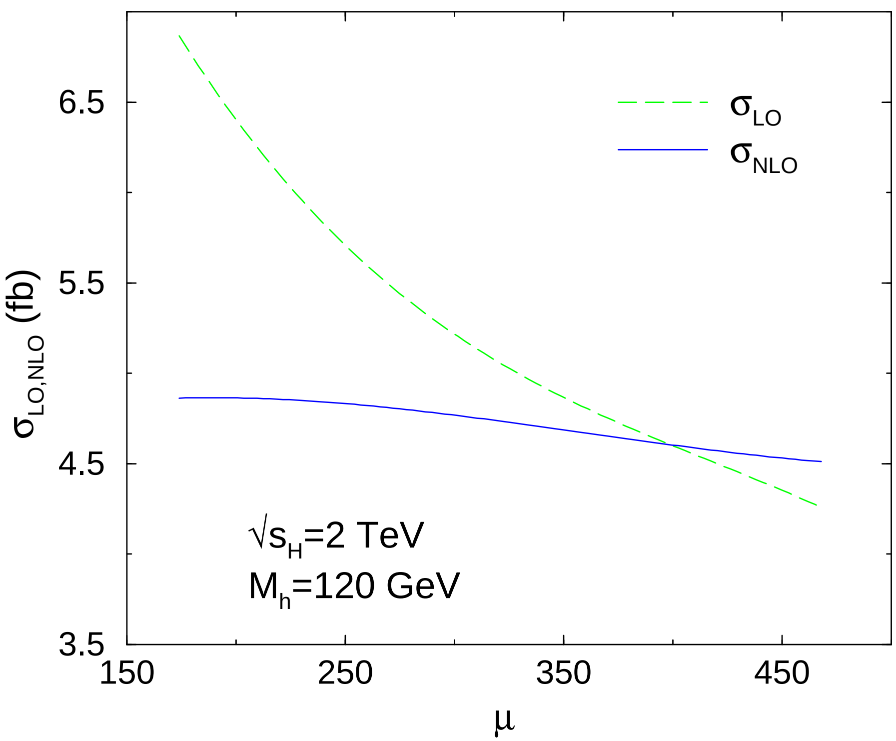


from L.Reina, S.Dawson, DW, PRD 65 (2002), S.Dawson, L.H.Orr, L.Reina, DW, PRD 67 (2003)

Main Result

Drastically reduced scale dependence of the total inclusive production cross sections:

$p\bar{p} \to t\bar{t}HX$ at the Tevatron



μ	σ_{LO} (fb)	σ_{NLO} (fb)
m_t	6.866(1)	4.86(3)
$m_t + M_h/2$	5.909(1)	4.85(2)
$2m_t$	4.879(1)	4.69(2)
$2m_t + M_h$	4.255(1)	4.51(2)

from L.Reina, S.Dawson, DW, PRD 65 (2002),

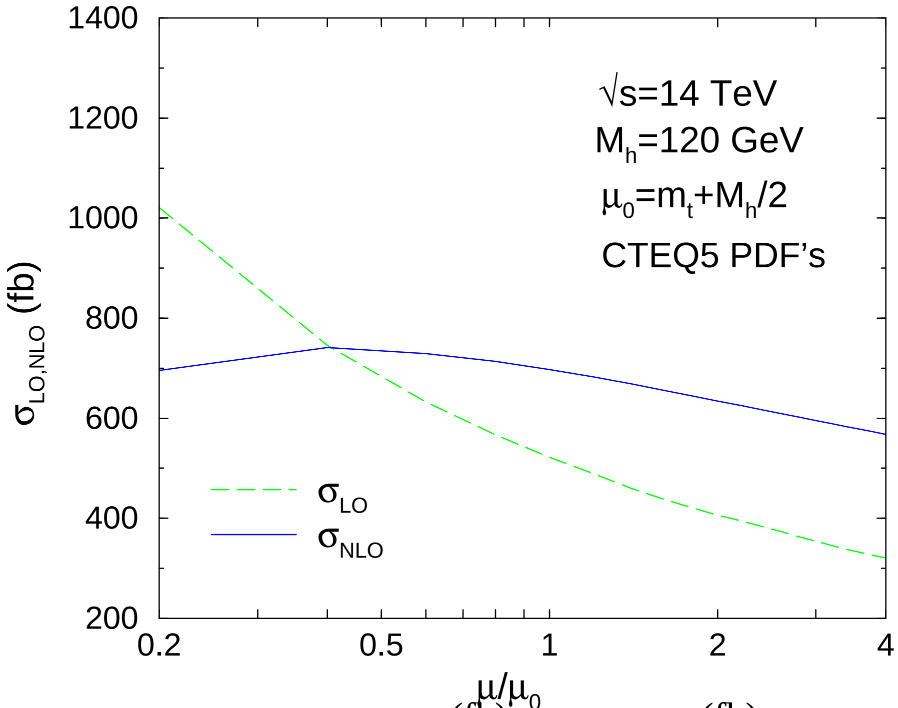
L.Reina, S.Dawson, PRL 87 (2001)

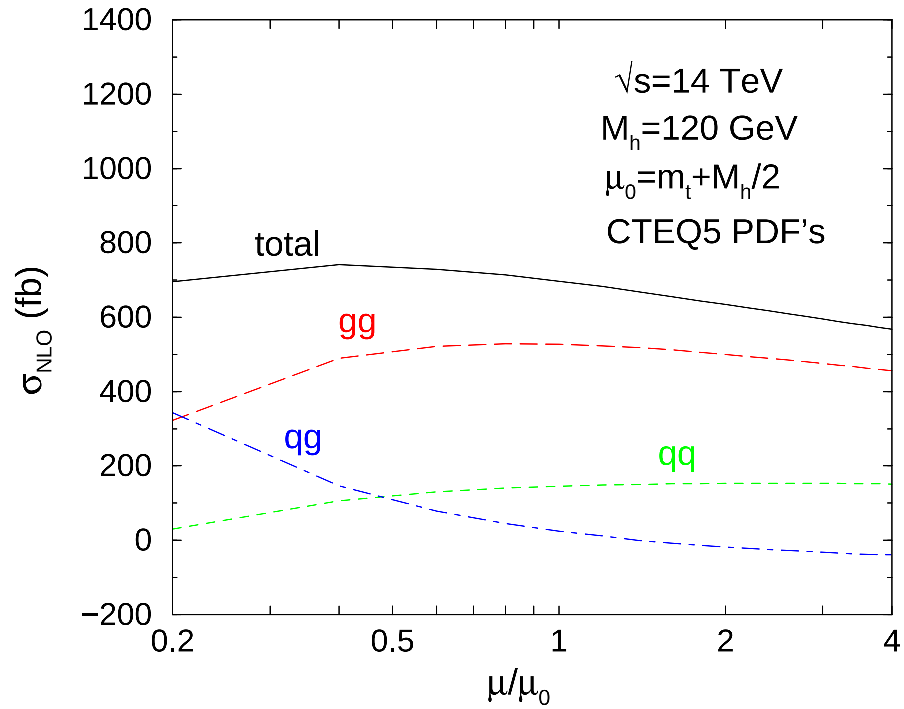
see also W.Beenakker *et al.*, PRL 87 (2001), NPB 653 (2003)

Main Result

Drastically reduced scale dependence of the total inclusive production cross sections:

$pp \to t\bar{t}HX$ at the LHC





μ	σ_{LO} (fb)	σ_{NLO} (fb)
m_t	582.92(6)	719(4)
$m_t + M_h/2$	520.47(6)	697(3)
$2m_t$	450.09(5)	663(3)
$2m_t + M_h$	405.54(4)	634(2)

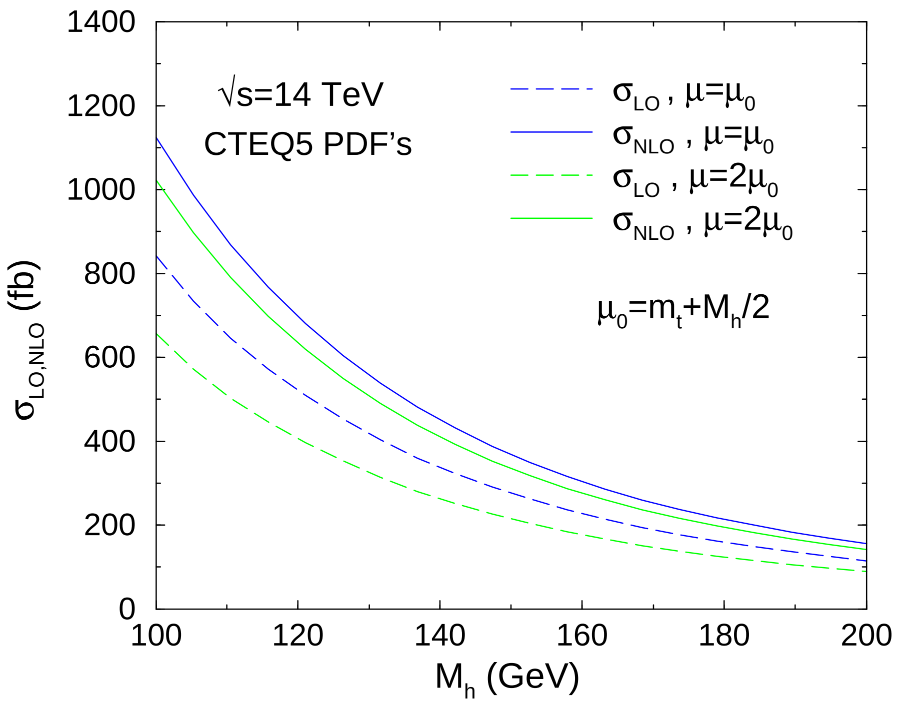
from S.Dawson, L.H.Orr, L.Reina, DW, PRD 67 (2003),

S.Dawson, C.Jackson, L.H.Orr, L.Reina, DW, PRD 68 (2003)

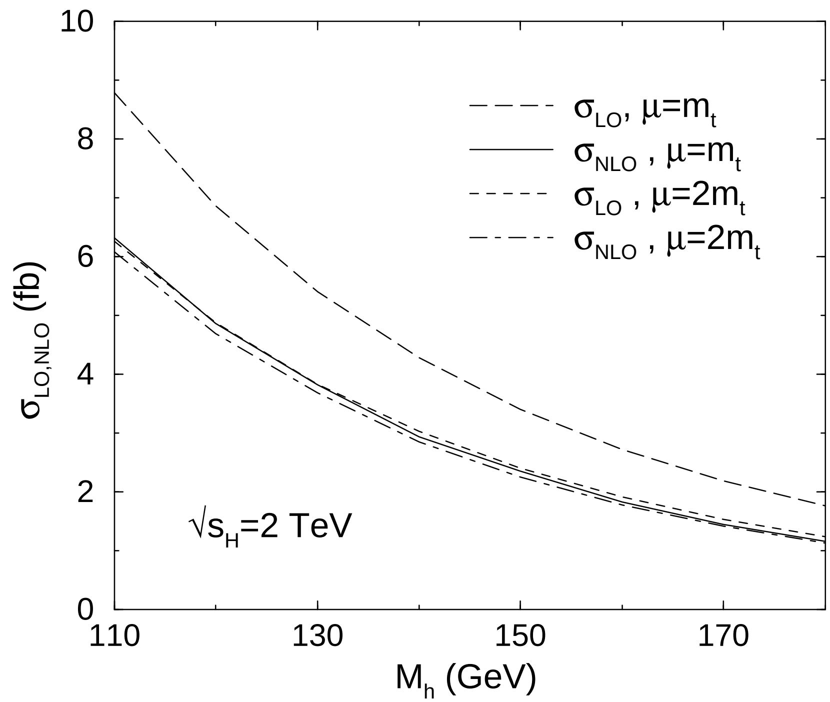
see also W.Beenakker *et al.*, PRL 87 (2001), NPB 653 (2003)

M_H dependence

$pp \to t\bar{t}HX$ at the LHC



$p\bar{p} \to t\bar{t}HX$ at the Tevatron



from S.Dawson, L.H.Orr, L.Reina, DW, PRD 67 (2003), L.Reina, S.Dawson, DW, PRD 65 (2002)

S.Dawson, C.Jackson, L.H.Orr, L.Reina, DW, PRD 68 (2003)

see also W.Beenakker *et al.*, PRL 87 (2001), NPB 653 (2003)

Summary for $t\bar{t}h$

- $t\bar{t}H$ is a very interesting production mode at the LHC:
  - discover/confirm the Higgs
  - measurement of Top Yukawa coupling
  - SM? New Physics?
- It is crucial to know the impact of QCD corrections.
- The NLO inclusive total cross section to $p\bar{p} \to t\bar{t}H$ at the Tevatron and $pp \to t\bar{t}H$ at the LHC has been calculated independently by two groups:

  $\sigma_{\rm NLO}(p\bar{p} \to t\bar{t}H)$: W.Beenakker *et al.*, PRL 87 (2001)

  L.Reina, S.Dawson, PRL 87 (2001), L.Reina, S.Dawson, DW, PRD 65 (2002)

  $\to$ The two calculations are in good agreement.

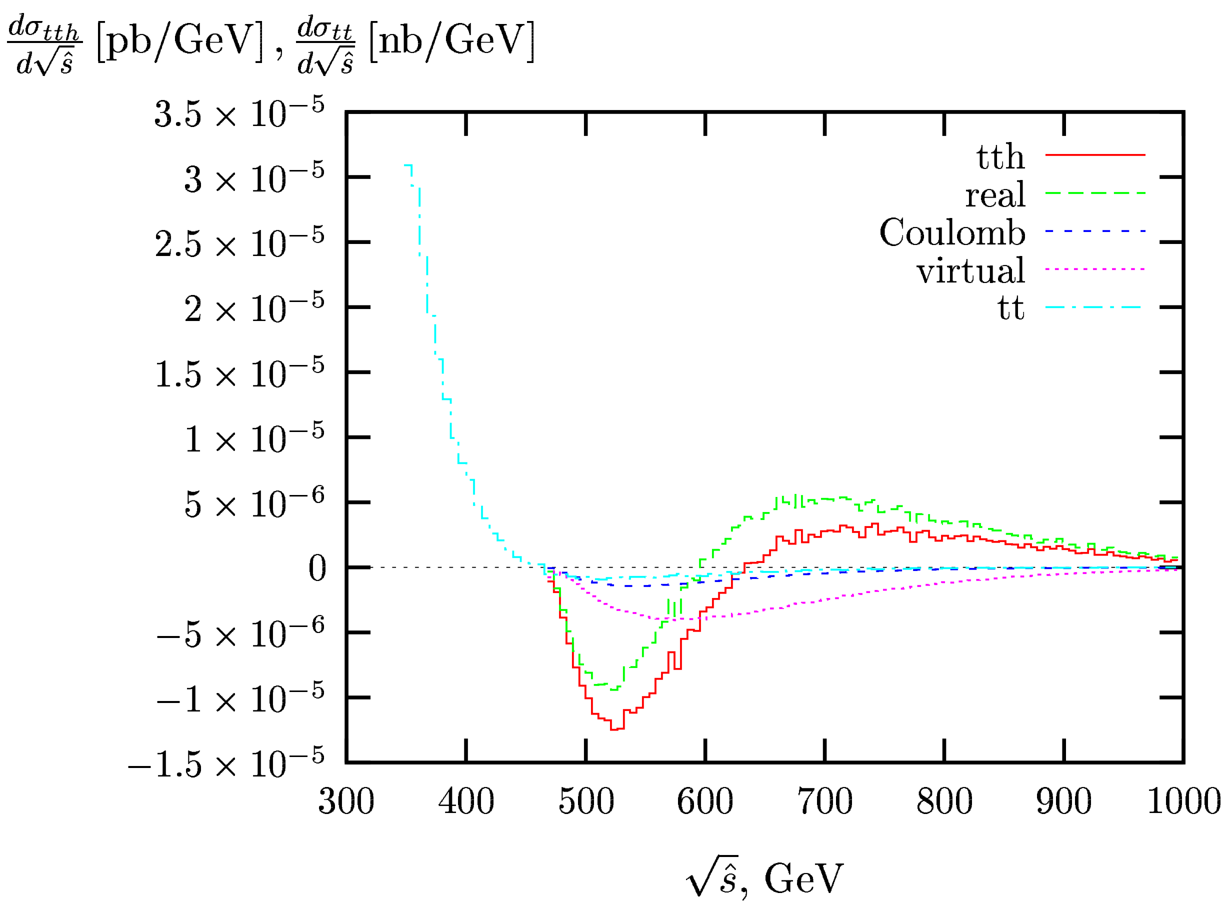
  $\sigma_{\rm NLO}(pp \to t\bar{t}H)$: W.Beenakker *et al.*, PRL 87 (2001)

  S.Dawson, L.H.Orr, L.Reina, DW, PRD 67 (2003), S.Dawson, C.Jackson, L.H.Orr, L.Reina, DW, PRD 68 (2003)

  $\to$ The two calculations are in good agreement.

- At NLO the factorization/renormalization scale dependence is strongly reduced.
- The remaining theoretical uncertainty from μ variation is estimated to be about $10-15\%$(Tevatron) and $15-20\%$ (LHC).
- At the Tevatron the $\mathcal{O}(\alpha_s)$ corrections slightly reduce $\sigma_{\rm LO}$ for $m_t < \mu < 2m_t$ ($K = 0.7 - 0.95$).
- At the LHC the $\mathcal{O}(\alpha_s)$ corrections slightly enhance $\sigma_{\rm LO}$ for $m_t + M_H/2 < \mu < 4m_t + 2M_H$ ($K = 1.2 - 1.4$).
- Possible improvement: Resummation of large logarithmic corrections at the $t\bar{t}h$ threshold.

$\frac{d\sigma_{t\bar{t}H}}{d\sqrt{\hat{s}}}$ and $\frac{d\sigma_{t\bar{t}}}{d\sqrt{\hat{s}}}$ at the Tevatron when only including $\mathcal{O}(\alpha_s)$ corrections:



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

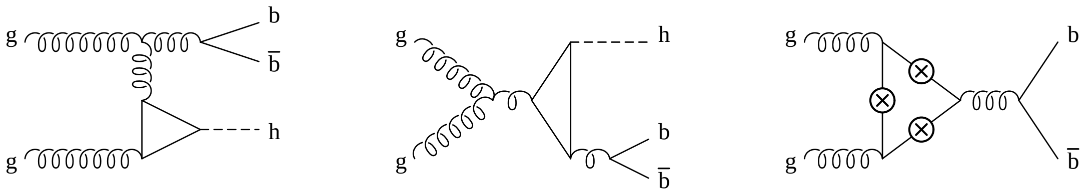
$gg, q\bar{q} \to b\bar{b}h$ at pp and $p\bar{p}$ colliders is dominated by the gg initiated process.

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.

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.

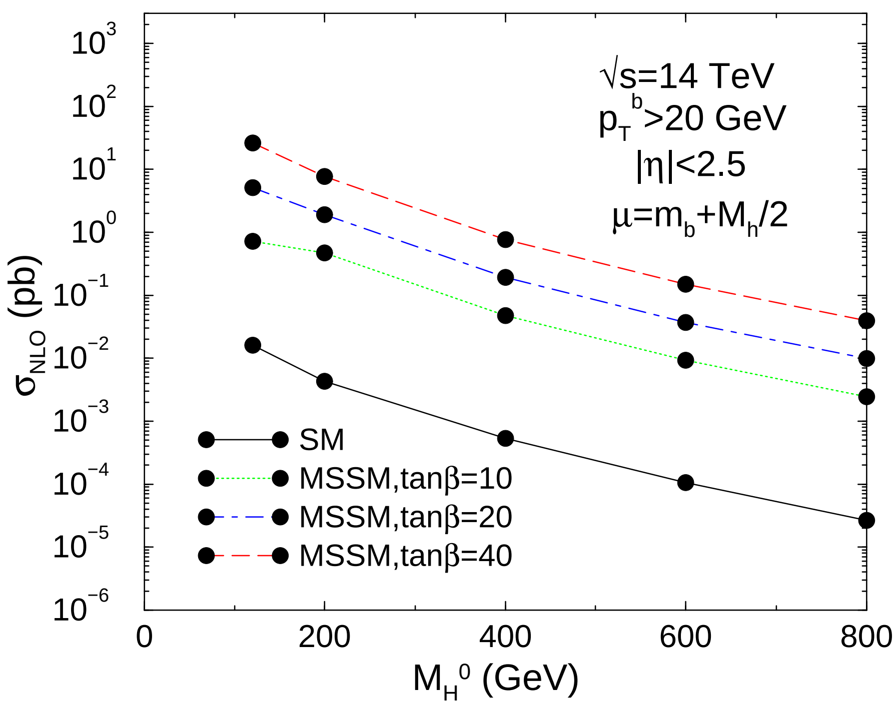
→ Unambiguously proportional to the b quark Yukawa coupling.

Status:

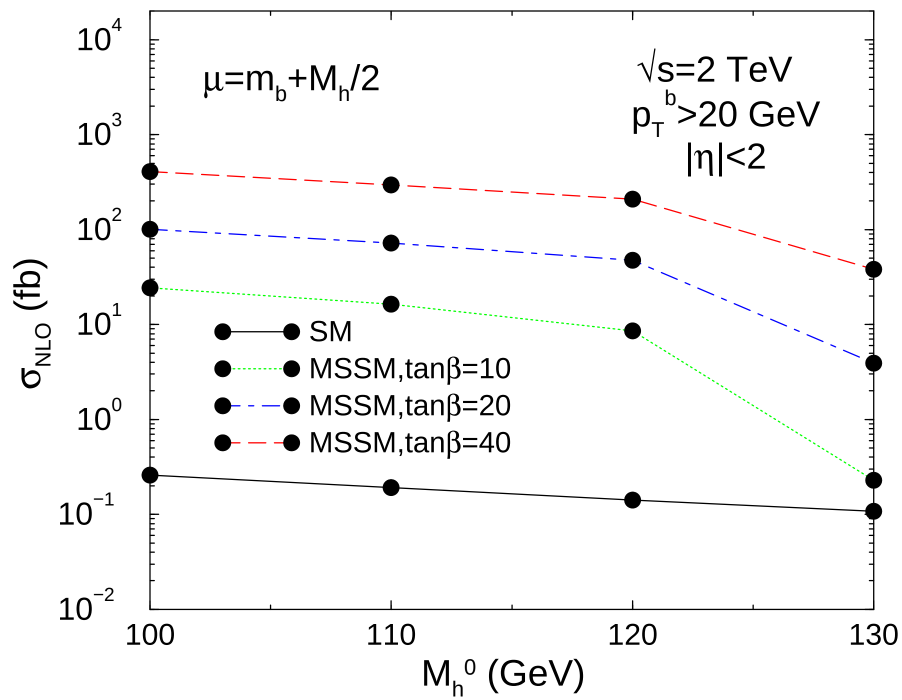
Two independent calculations based on $gg, q\bar{q} \to b\bar{b}h$ at NLO QCD by S.Dittmaier, M.Krämer, M.Spira (hep-ph/0309204) and S.Dawson, C.Jackson, L.Reina, D.W. (PRD 69 (2004)). They are in good agreement.

$M_{(h^0,H^0)}$, $\tan\beta$ 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)

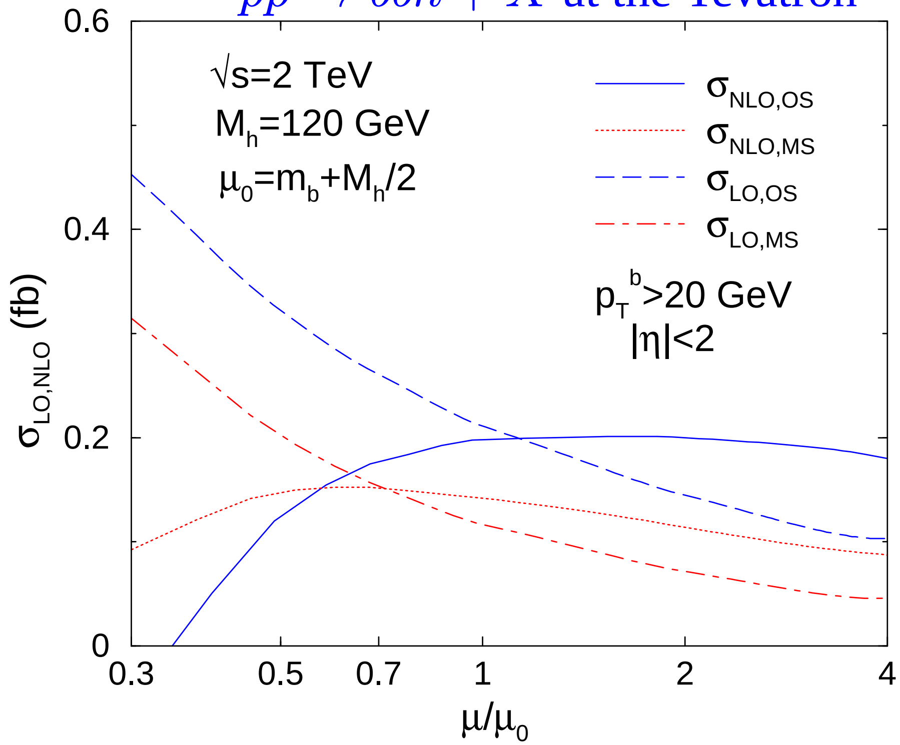
To a good approximation the MSSM result can be obtained from the SM result as follows:

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

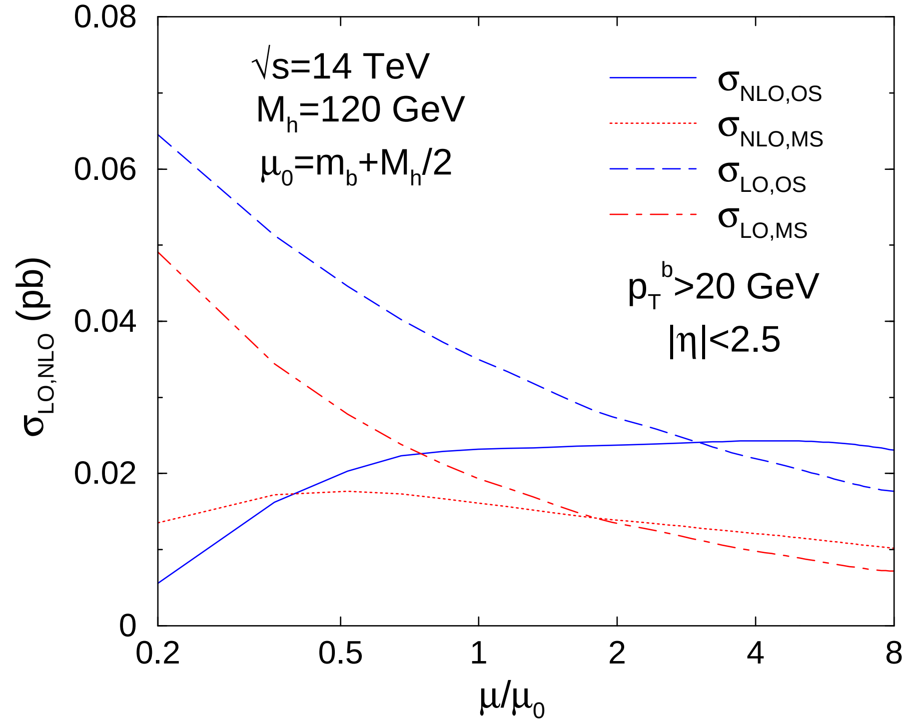
Main Result

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

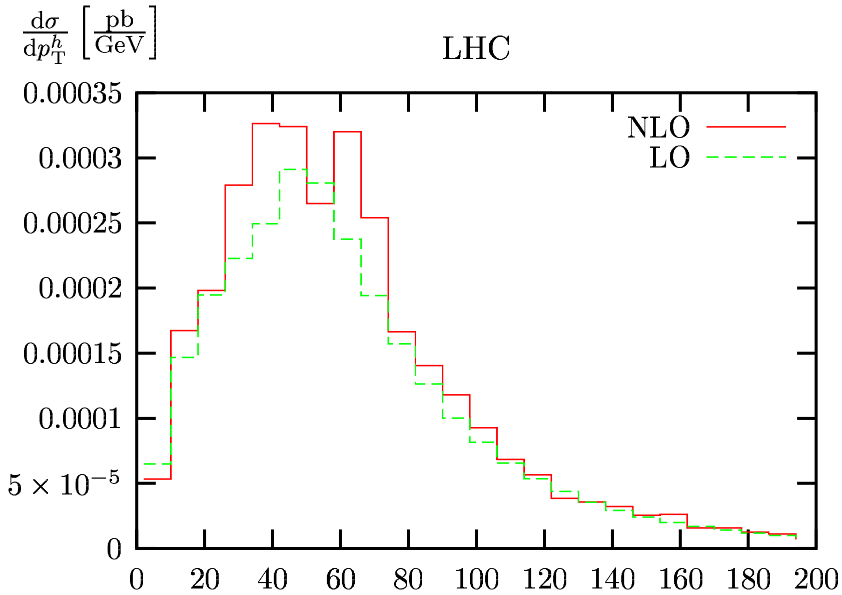


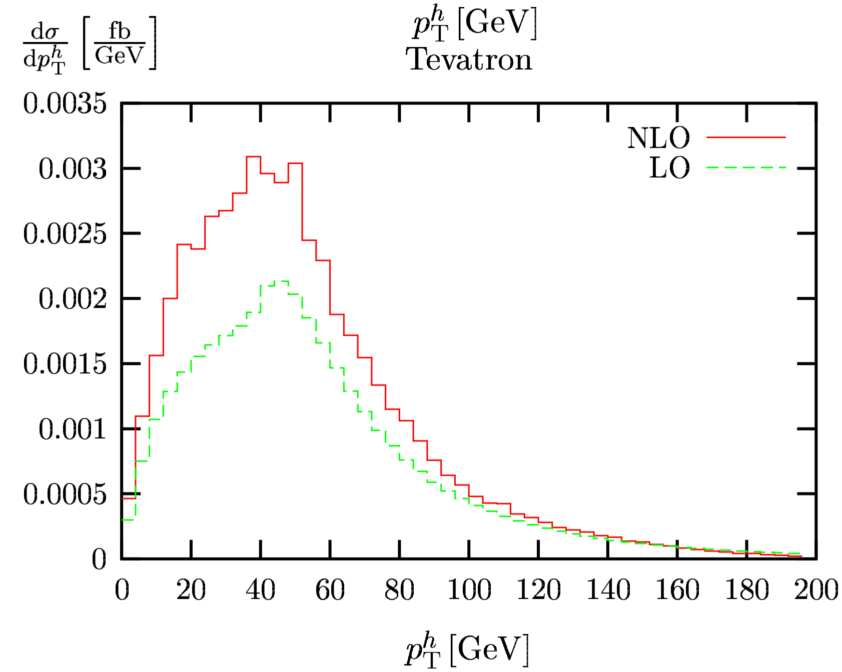
from S.Dawson, C.Jackson, L.Reina, D.W., PRD 69 (2004)

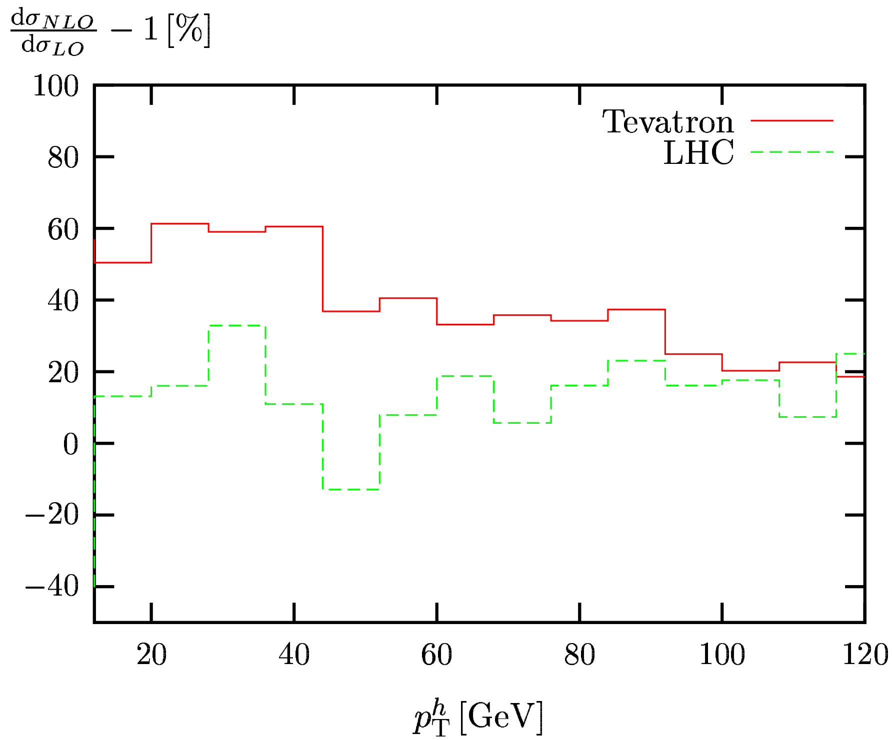
see also S.Dittmaier *et al.*, hep-ph/0309204 and J.Campbell *et al.* in LesHouches 2003 proceedings, hep-ph/0405302

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 *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 $gg, q\bar{q} \to b\bar{b}h$.

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

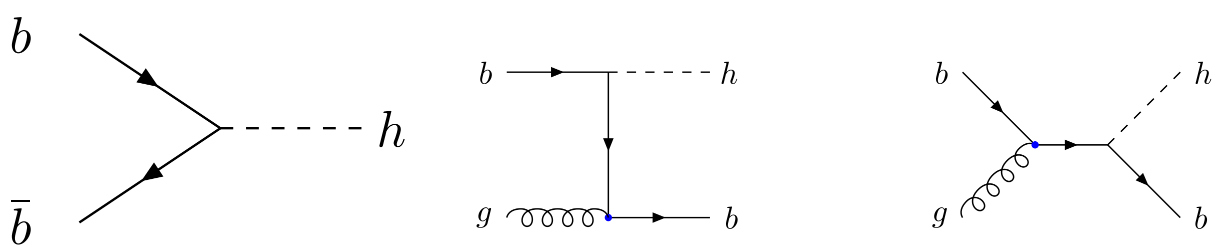
Use of b quark PDFs to sum to all orders large logs, $\alpha_s \ln(m_b^2/\mu_F^2)$ ($\mu_F \approx M_h$), which arise due to initial-state $g \to b\bar{b}$ splitting.

→ VFS 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.

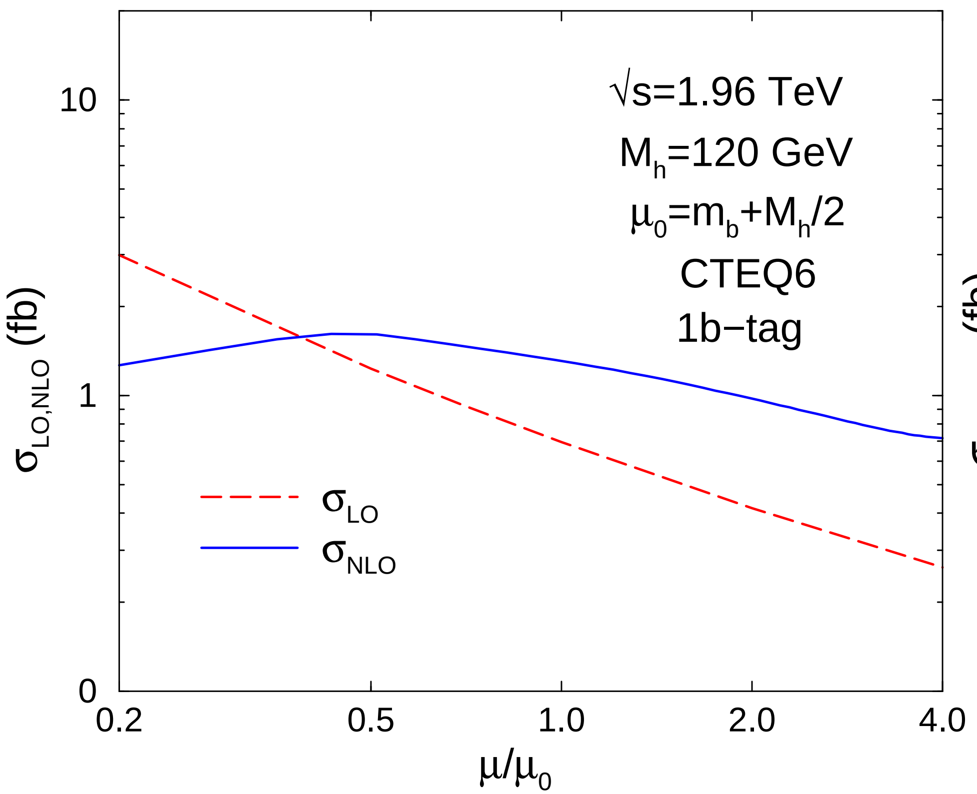
Semi-inclusive (1 b-tagged): known at NLO QCD

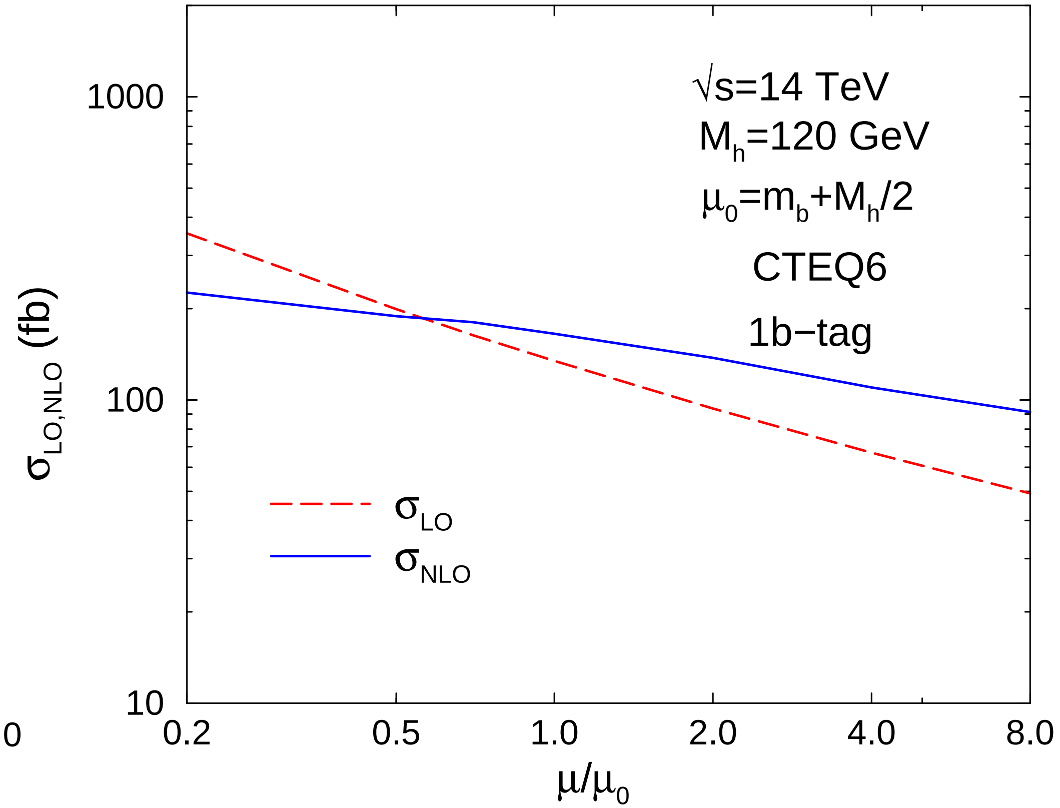
$b(\bar{b})g \to b(\bar{b})h$ is the leading order subprocess of $\mathcal{O}(\alpha_s^2 \ln(M_h/m_b))$ and $gg, q\bar{q} \to b\bar{b}h$ are identified as NLO contributions of $\mathcal{O}(1/\ln(M_h/m_b))$.

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

Main Result

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



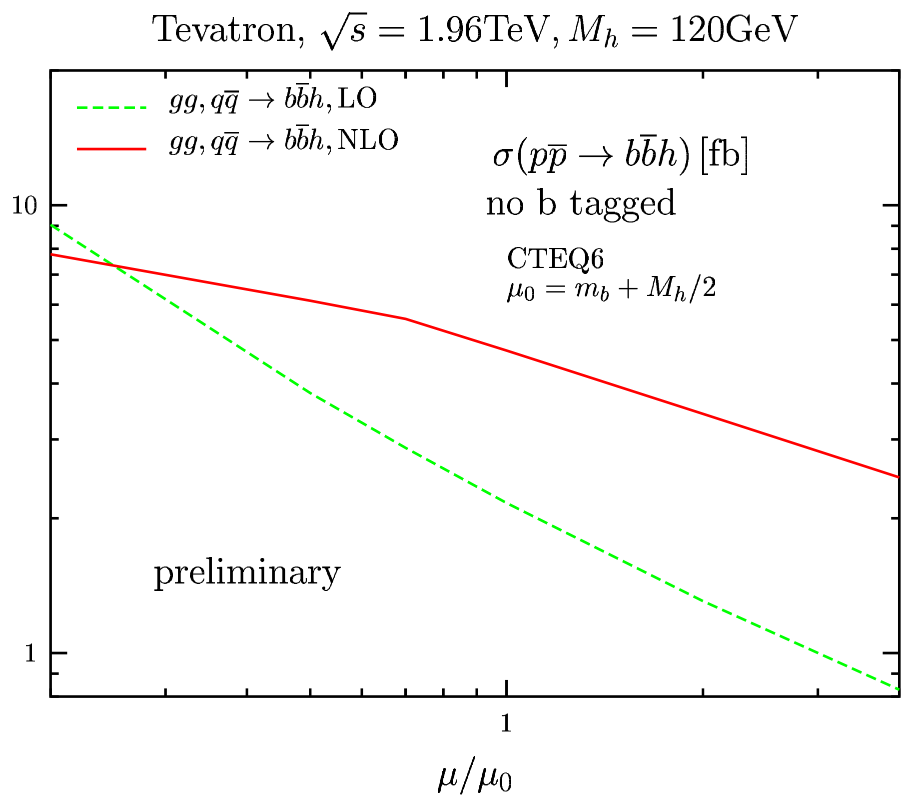


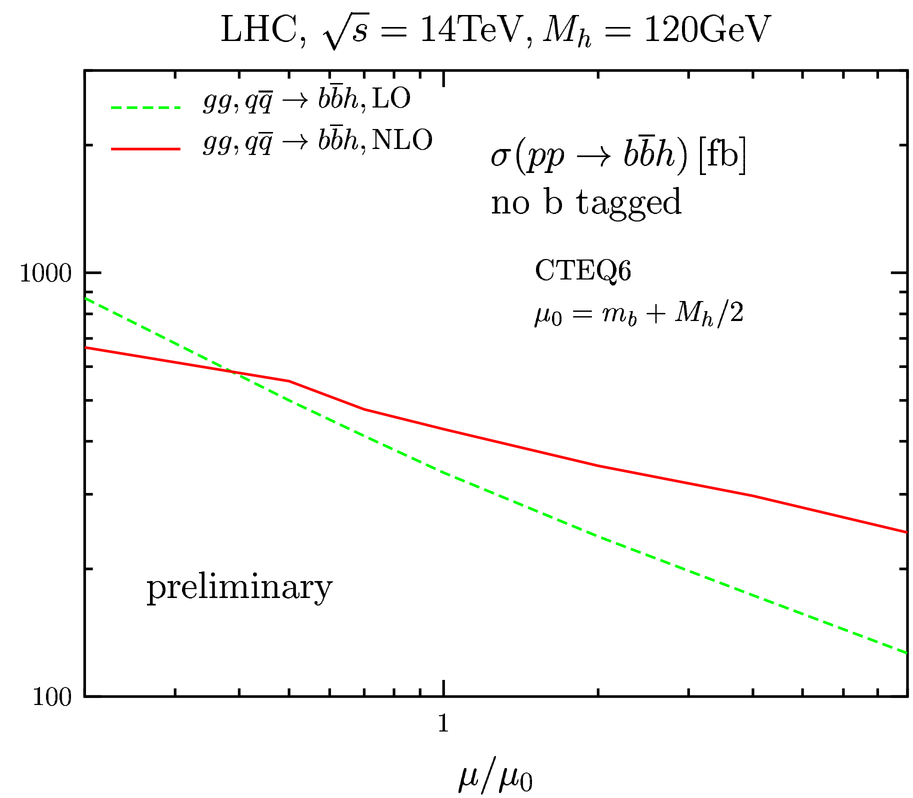
from S.Dawson, C.Jackson, L.Reina, D.W., hep-ph/0408077

see also S.Dittmaier *et al.*, hep-ph/0309204 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:



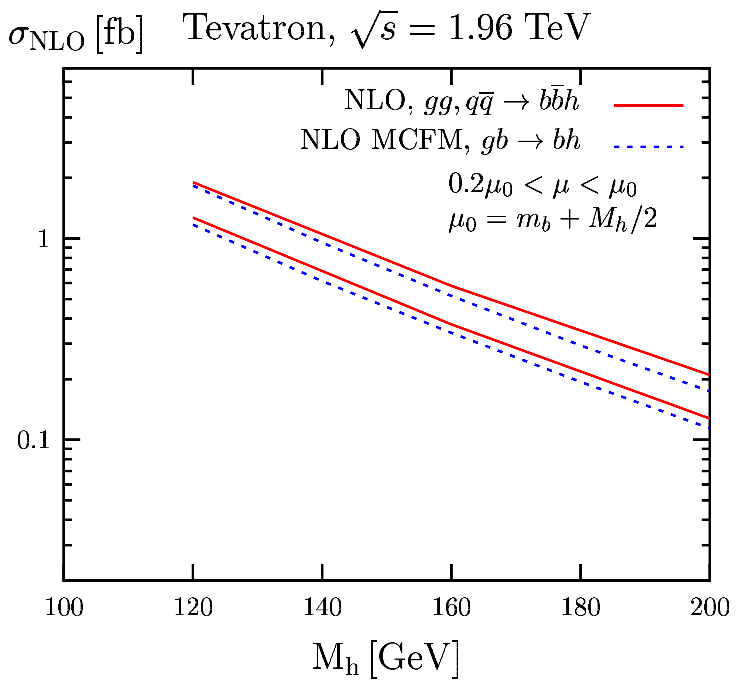


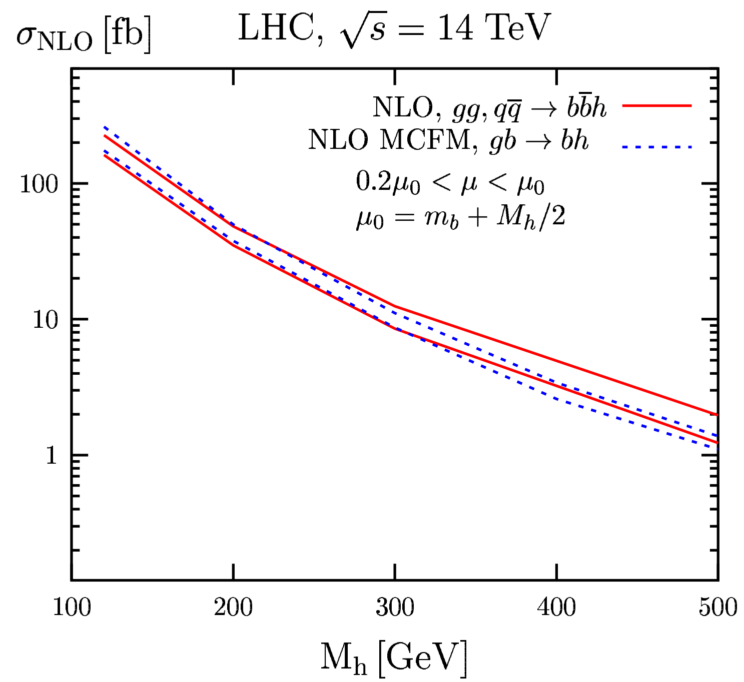
from S.Dawson, C.Jackson, L.Reina, D.W., in prep.

see also S.Dittmaier *et al.*, hep-ph/0309204 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:





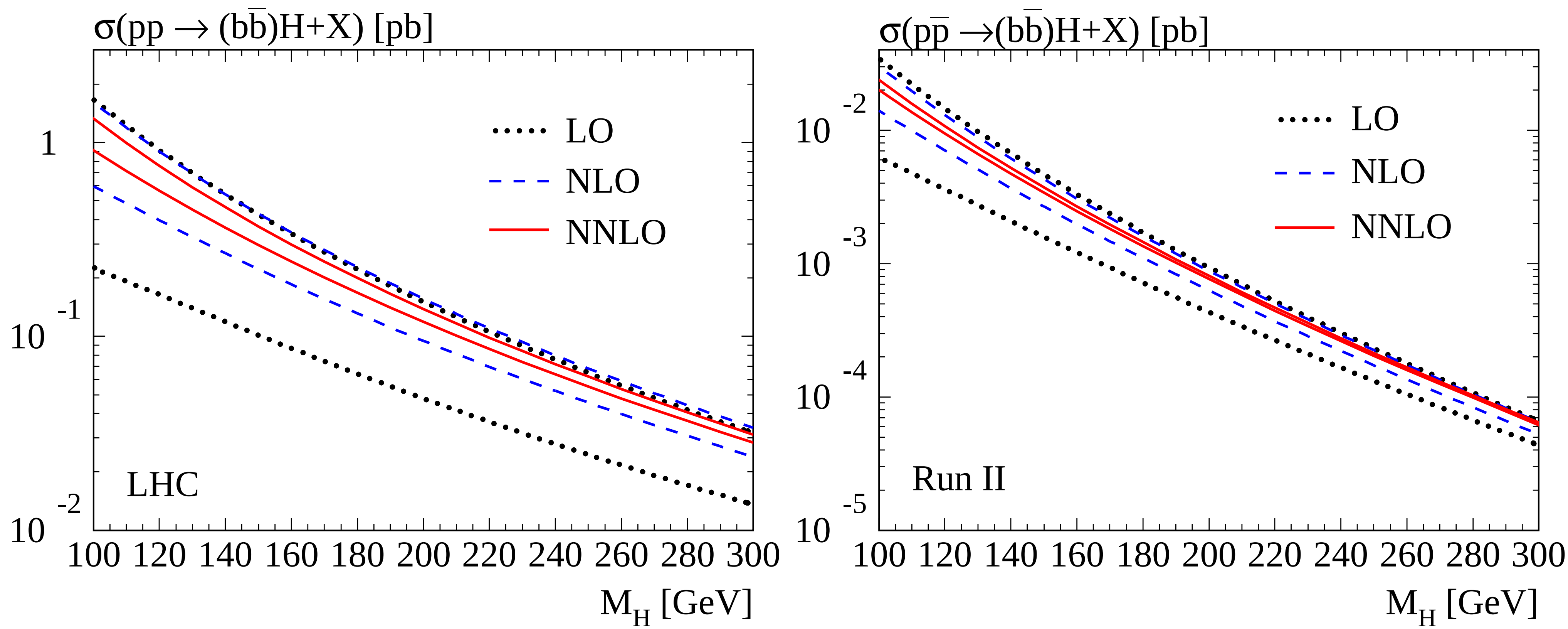
$gg, q\bar{q} \to b\bar{b}h$: from S.Dawson, C.Jackson, L.Reina, D.W., hep-ph/0408077, see also S.Dittmaier *et al.*, hep-ph/0309204

$gb(\bar{b}) \to b(\bar{b})h$: 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))

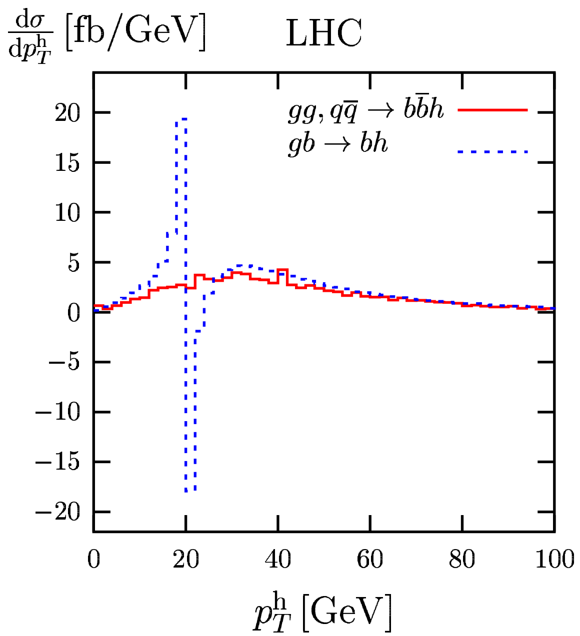
M_h dependence – 0 b tagged (VFS)

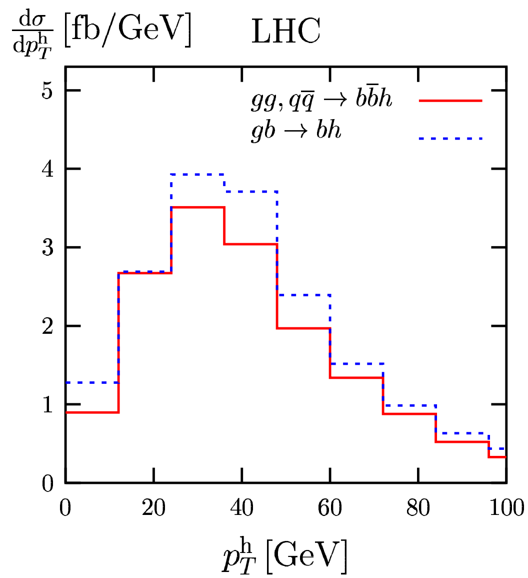
from R.Harlander, W.Kilgore, Phys.Rev. D68 (2003) 013001

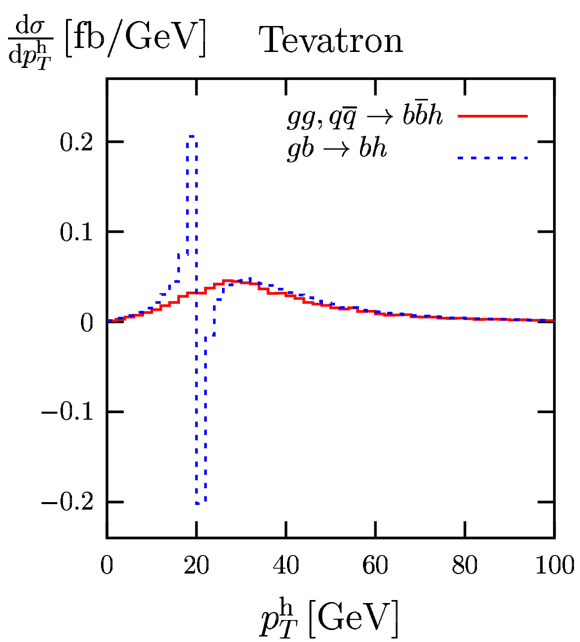


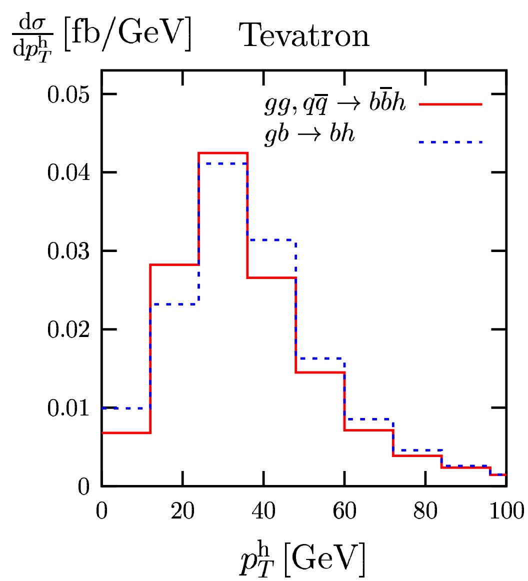
$\mu_F = (0.1, 0.7)M_h, \mu_R = M_h$

Effect of NLO QCD corrections on the Higgs p_T distribution:



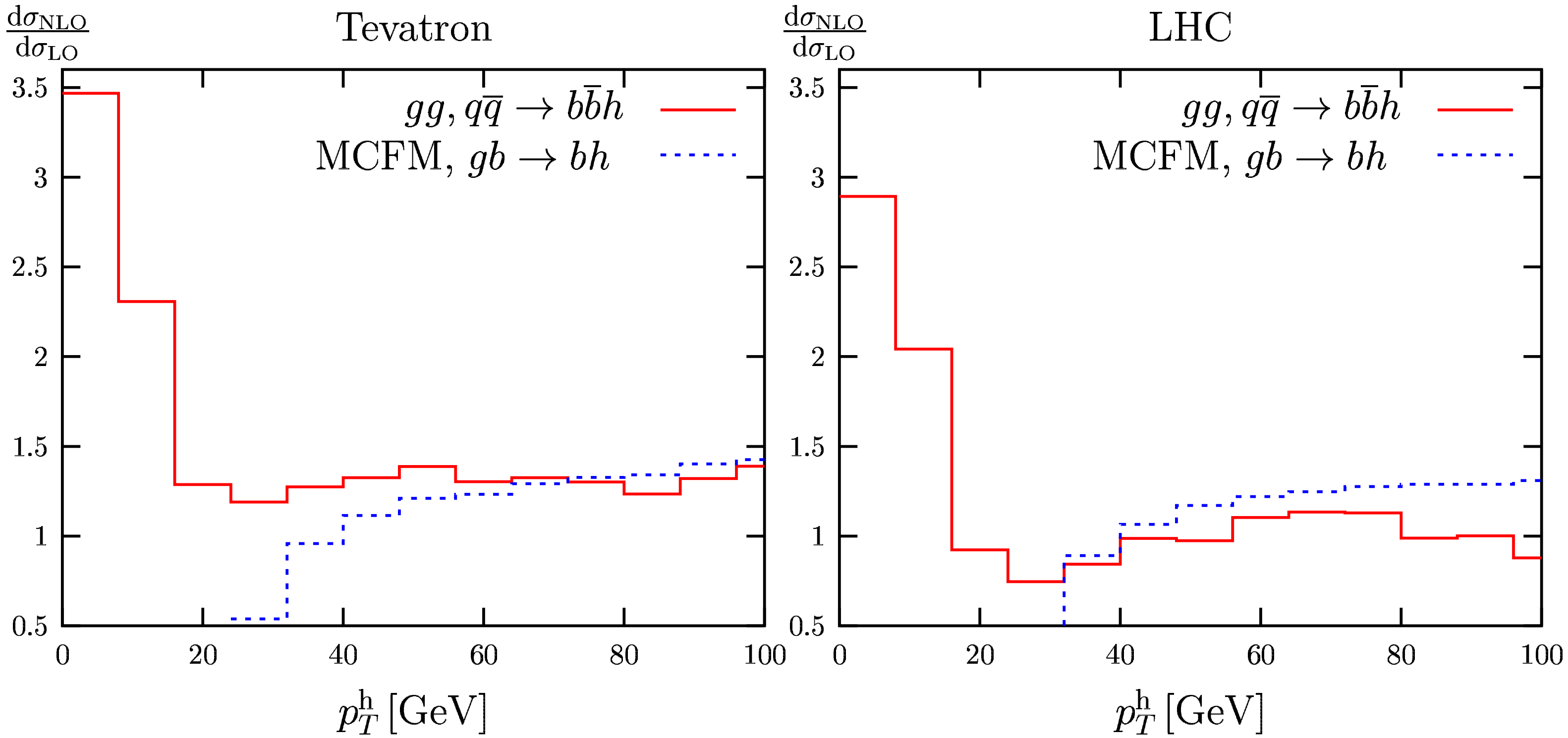






from S.Dawson, C.Jackson, L.Reina, D.W., hep-ph/0408077

Effect of NLO QCD corrections on the Higgs p_T distribution:



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

Summary for $b\bar{b}h$

- $b\bar{b}h$ 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, hep-ph/0405302 and S.Dawson *et al*, hep-ph/0408077):

  $\rightarrow$ 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:

    $\rightarrow$ The two calculations are in good agreement.

    $\rightarrow$ Results have been obtained for the inclusive, semi-inclusive and exclusive case.

$\rightarrow$ 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 (VFS).

  $\rightarrow$ 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.

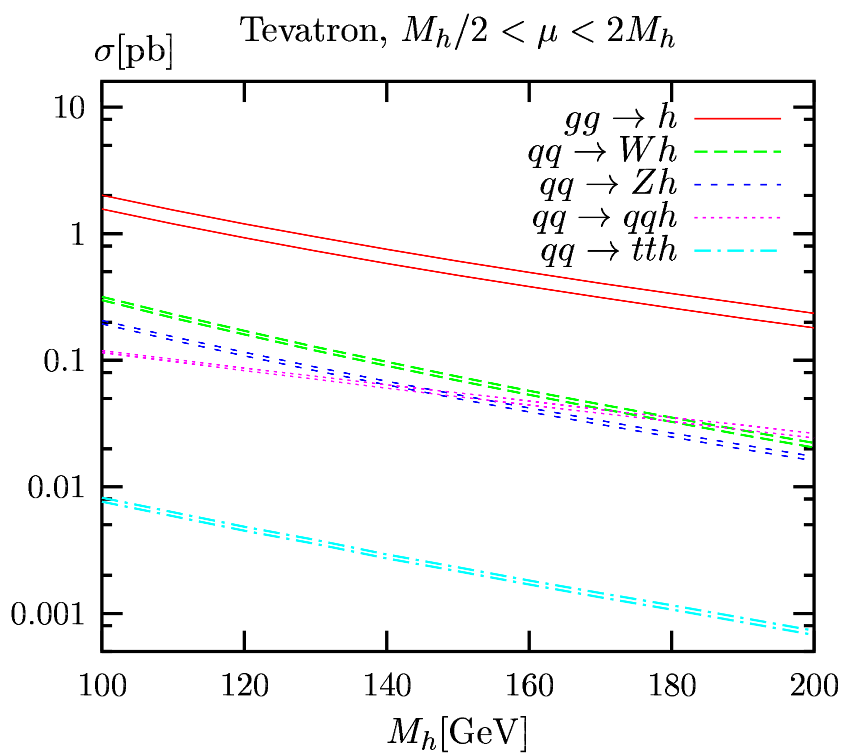
- Inclusive $(b\bar{b})h$ production based on b quark fusion, $b\bar{b} \rightarrow h$, is known at NNLO QCD (VFS).

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

- Possible improvement (FFS):
  Identification and resummation of large logarithms, $\ln(M_h/m_b)$, arising when integrating over the b quark p_T.
  Inclusion of SUSY loop corrections.

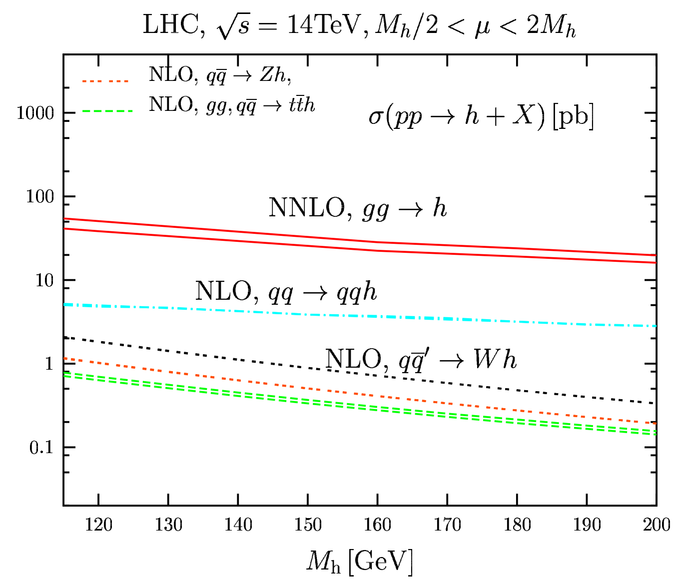
Conclusion

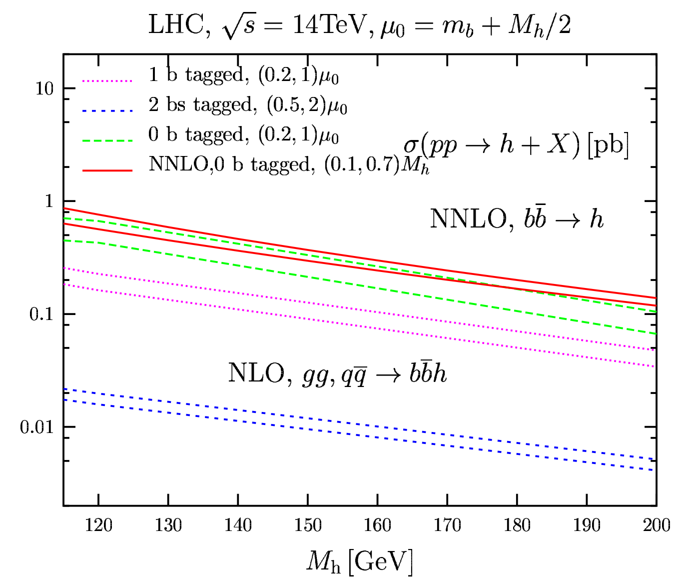
QCD predictions for total cross sections to Higgs production processes at hadron colliders are under good theoretical control:



from S.Dawson *et al.*, hep-ph/0210109

$t\bar{t}h$: μ varied between $\mu_0 = m_t + M_h/2$ and $2\mu_0$.





from S.Dawson *et al.*, in prep. (prelim.)