QCD $\mathcal{O}(\alpha_s)$ corrections to associated $t\bar{t}H$ at hadron colliders

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I. Motivation

The Higgs boson – a direct consequence of W and Z mass generation in the Standard Model via spontaneous symmetry breaking of the $SU(2)_L \otimes U(1)_Y$ 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.

Where is the SM Higgs ?

We know from direct (LEP2) and indirect searches (EWK fits) that LHWG Note/2001-03, LEPEWWG Note/2001-02

$$114.1\,\text{GeV} < M_H \lesssim 200\,\text{GeV}$$

Higgs discovery reach at the Tevatron Run II ($15\,\text{fb}^{-1}$):

$$M_H \lesssim 180\,\text{GeV}$$

Higgs searches at the Tevatron are challenging:

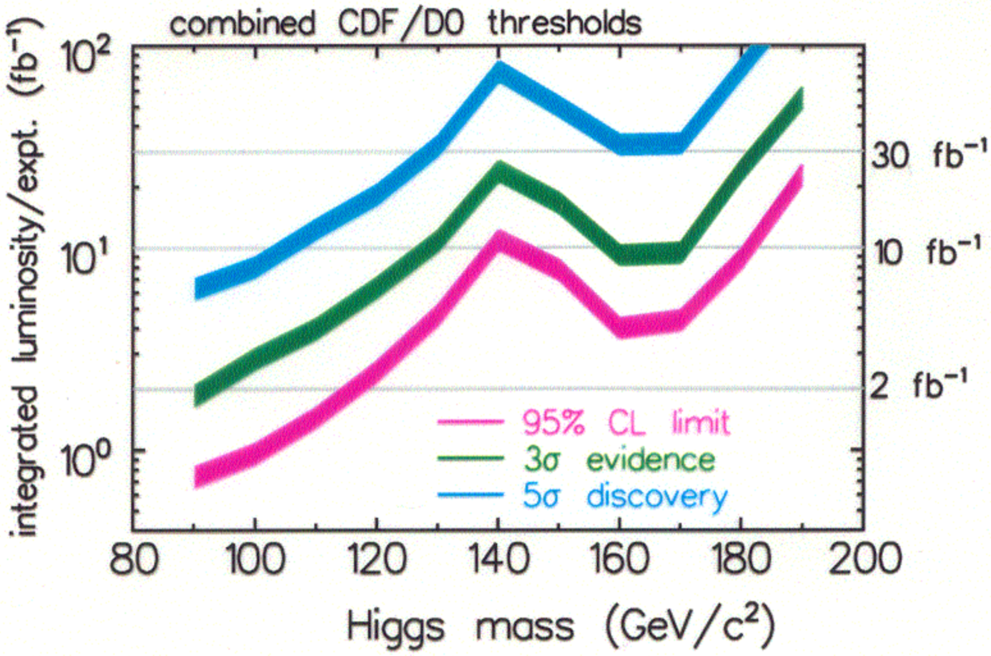
Dominant production modes: $q\bar{q} \to WH, ZH; gg \to H$

Dominant decay modes:

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

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

J.D.Hobbs, hep-ph/9903494
M.Carena *et al.*, hep-ph/0010338



All possible production channels need to be explored, e.g.

$$p\bar{p} \to t\bar{t}H$$

low event rate but spectacular signature: $WWb\bar{b}b\bar{b}$

Including $t\bar{t}H$ production could yield a 15-20% reduction in the luminosity threshold for discovery at $M_H = 120$ GeV.

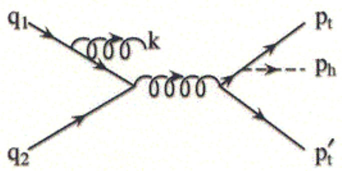
J. Incandela (FNAL, May 2001), J.Goldstein et al, Phys.Rev.Lett.86 (2001)

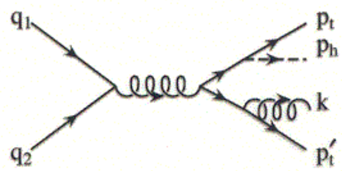
two groups: W. Beenakker et al., PRL 87 (2001)
L. Reina et al, PRL 87(2001), PRD 65(2002)

QCD corrections to $t\bar{t}H$ production at the Tevatron

At NLO in α_s the cross section for $p\bar{p} \to t\bar{t}H$ includes virtual and real gluon radiation:

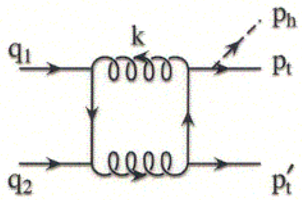
Examples of real $\mathcal{O}(\alpha_s)$ corrections to $p\bar{p} \to t\bar{t}H$



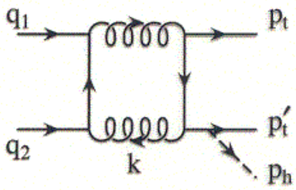


more than 95% of σ_{LO} from $q\bar{q} \to t\bar{t}H$

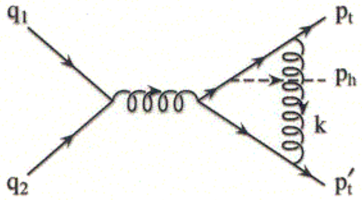
Examples of virtual $\mathcal{O}(\alpha_s)$ corrections to $p\bar{p} \to t\bar{t}H$



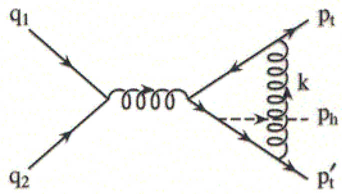
$B5^{(1)}$



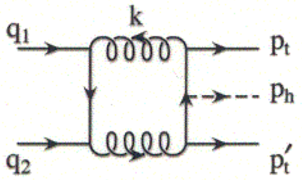
$B5^{(3)}$



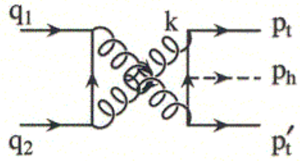
$B3^{(1)}$



$B3^{(2)}$



P1



P2

NLO total inclusive cross section for $p\bar{p} \to t\bar{t}H$:

$$\sigma_{NLO} = \sum_q \int dx_1 dx_2 \mathcal{F}_q^p(x_1) \mathcal{F}_{\bar{q}}^{\bar{p}}(x_2) \hat{\sigma}_{q\bar{q}}^{NLO}(x_1, x_2)$$

with the parton level cross section

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

$\hat{\sigma}_{virt}^{q\bar{q}}$:

- 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

$\hat{\sigma}_{real}^{q\bar{q}}$:

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

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

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

$$\longrightarrow \quad \text{two cut-off method}^{*}: \begin{cases} \delta_s & , E_g < \delta_s \sqrt{s}/2 \\ \delta_c & , (1 - \cos\theta_{ig}) < \delta_c \end{cases}$$

$$\longrightarrow \quad \text{one cut-off method}^{**}: s_{min} \quad , s_{ig} < s_{min}$$

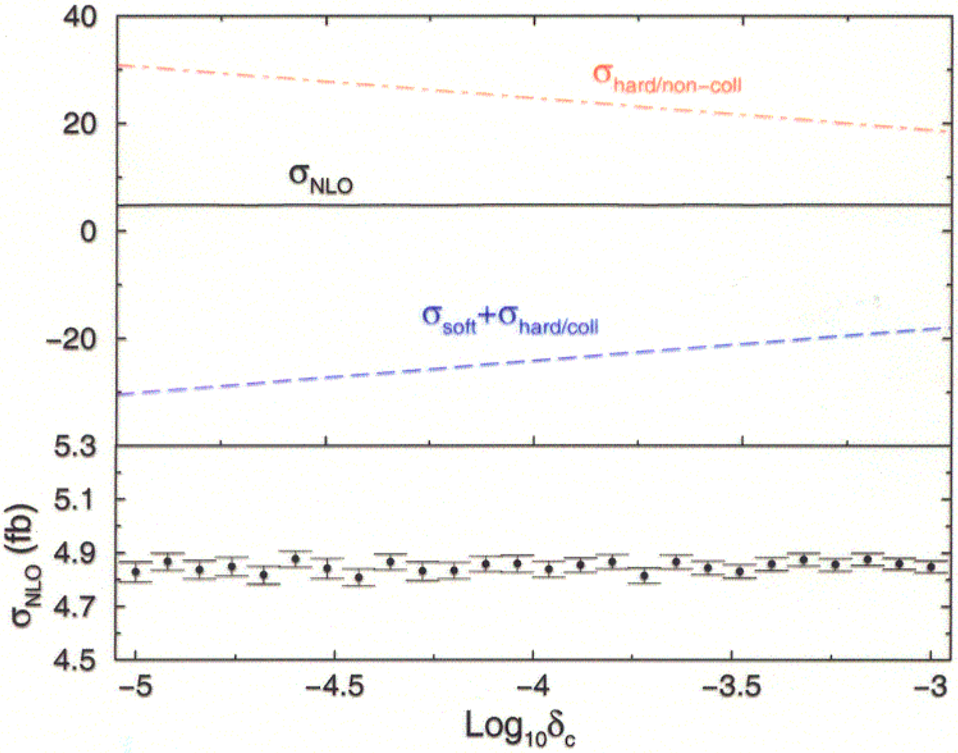
and compute $\hat{\sigma}^{q\bar{q}}_{real}$

- analytically below the cut-off(s)
- numerically above the cut-off(s).

* for a review see B. Harris and J. Owens, hep-ph/0102128

** W. Giele et al., PRD 46 (1992), NPB 403 (1993)
S. Keller and E. Laenen, PRD 59 (1999)

δ_c cut-off dependence cancels in σ_{NLO}:

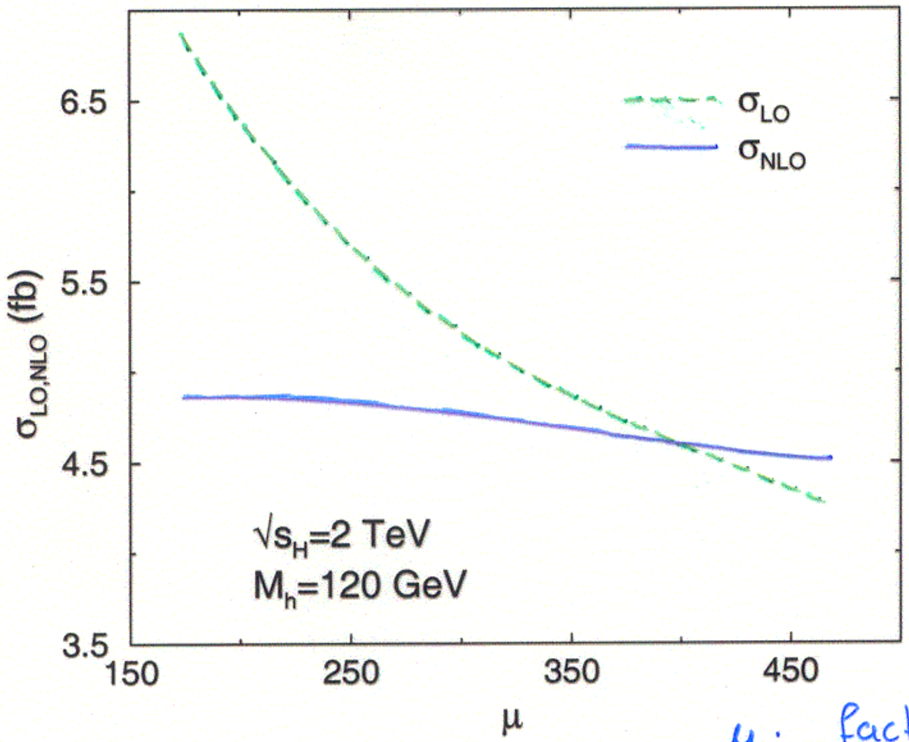


from L.Reina, S.Dawson and D.W., Phys.Rev.D65 (2002)

Main Result

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

$p\bar{p} \to t\bar{t}HX$ at the Tevatron (2 TeV)



μ	σ_{NLO} (fb)
m_t	4.86 ± 0.03
$m_t + M_h/2$	4.85 ± 0.02
$2m_t$	4.69 ± 0.02
$2m_t + M_h$	4.51 ± 0.02

μ: factorization scale = renormalization scale

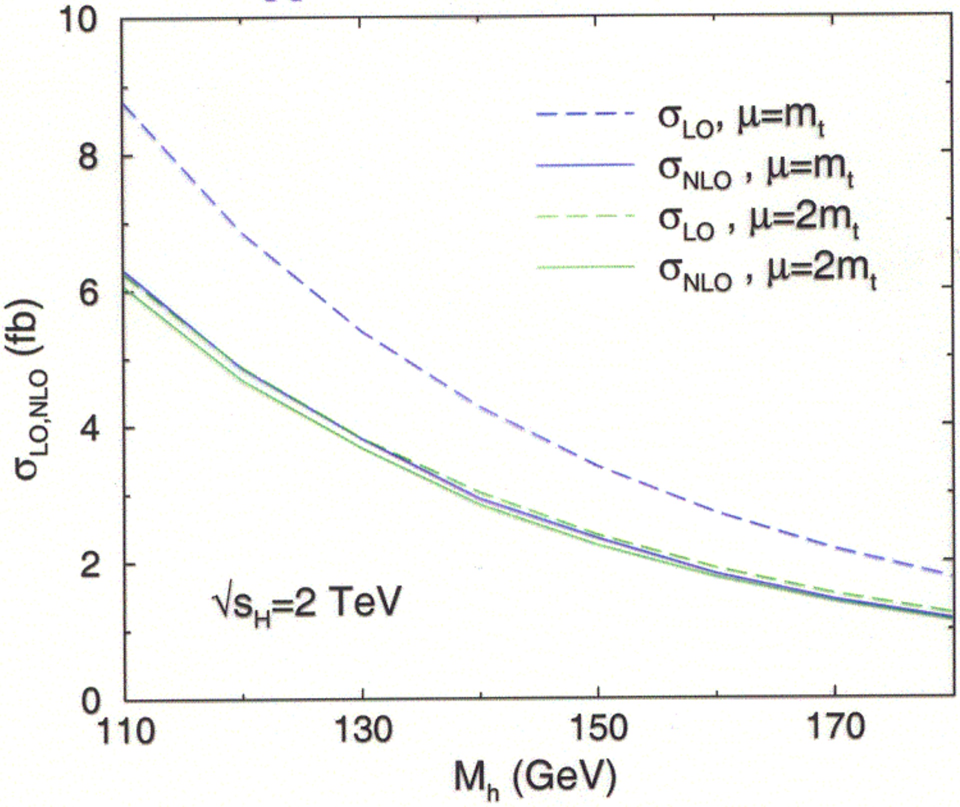
from L.Reina, S.Dawson and D.W., Phys.Rev.D65 (2002),

L.Reina and S.Dawson, Phys.Rev.Lett.87 (2001)

see also W.Beenakker et al., Phys.Rev.Lett.87 (2001)

Higgs mass dependence of the total inclusive production cross section:

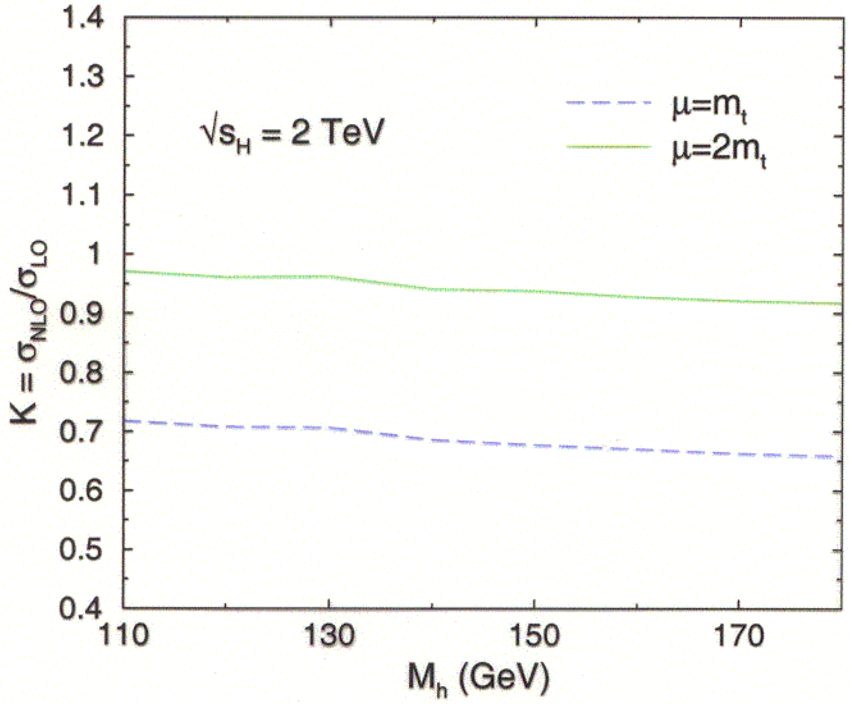
$p\bar{p} \to t\bar{t}HX$ at the Tevatron



from L.Reina, S.Dawson, and D.W., Phys.Rev.D65 (2002)

Results for σ_{NLO} vs σ_{LO}

$$p\bar{p} \to t\bar{t}HX$$



$\mu = m_t \ldots 2m_t + M_H$:

$M_H = 120$ GeV

$K_{q\bar{q}\to t\bar{t}H} = 0.7 - 1.0$

from L.Reina, S.Dawson, and D.W., Phys.Rev.D65 (2002)

Effective Higgs Approximation (EHA): S.Dawson, L.Reina

$M_H < \sqrt{s}$ and $M_H < m_t$, $\mu = m_t \ldots 2m_t + M_H$:

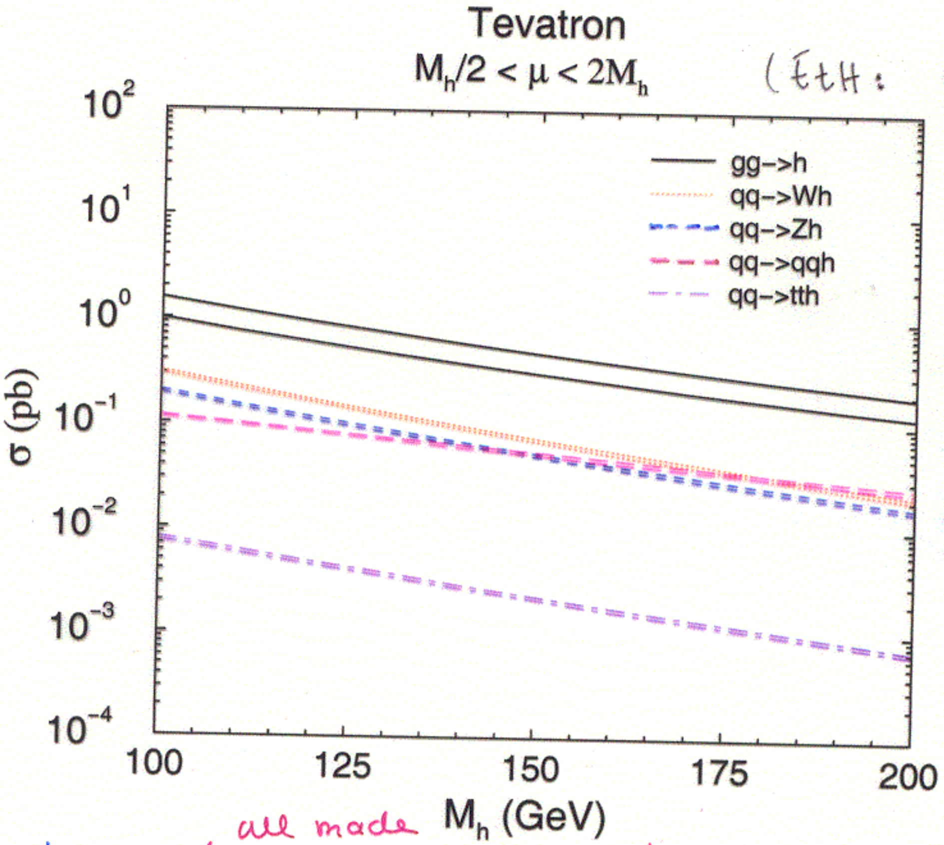
$$K_{EHA} \sim 0.6 - 0.7$$

$t\bar{t}$ production ($\mu = m_t$): P.Nason et al., W.Beenakker et al., R.Bonciani et al.

$$K_{q\bar{q}\to t\bar{t}} = 0.98$$

Scale dependence of σ_{NLO} at the Tevatron: (2 TeV)

($t\bar{t}H$: $m_t + \frac{M_H}{2} < \mu < 2m_t + M_H$)



σ_{NLO} by (all made publicly available by M. Spira)

$gg \to H$: S. Dawson, NPB359 (1991)
A. Djouadi, M. Spira, P. Zerwas, PLB 264 (1991)

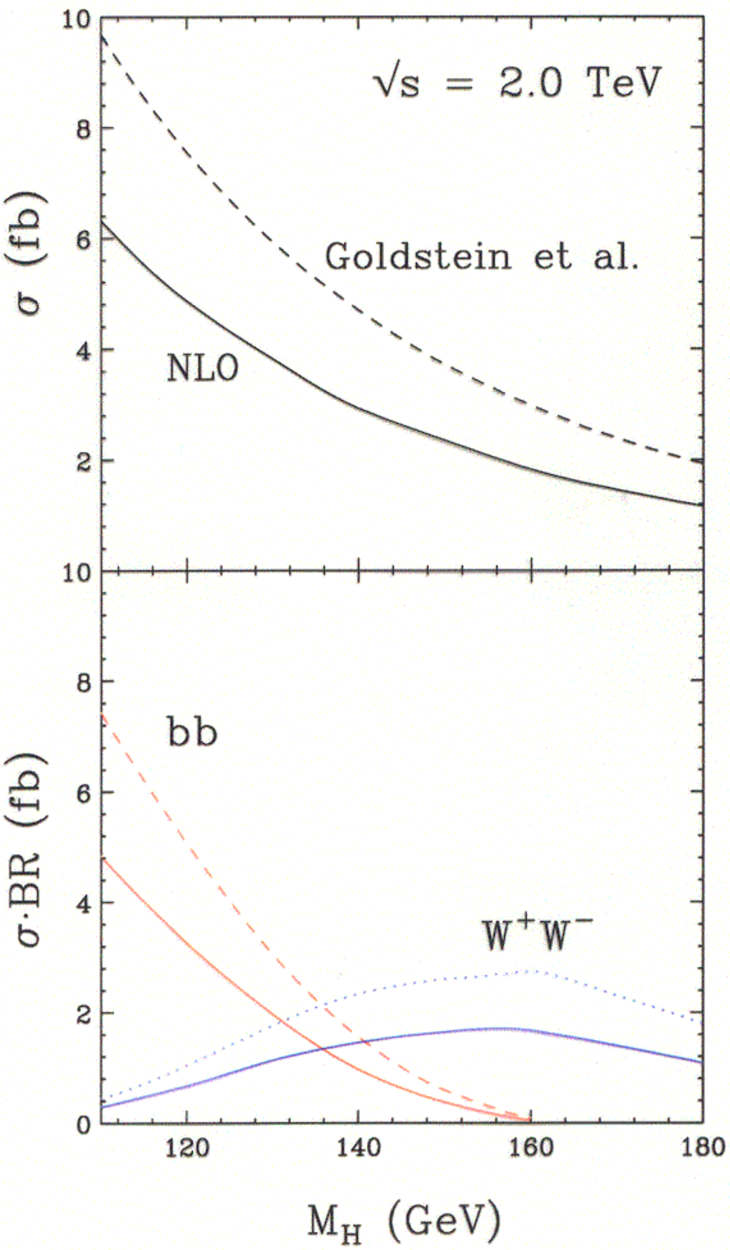
$q\bar{q} \to W,Z\,H$: T. Han, S. Willenbrock PLB273 (1991)

$q\bar{q} \to q\bar{q}H$: T. Han, G. Valencia, S. Willenbrock, PRL69 (1992)

$q\bar{q} \to t\bar{t}H$: W. Beenakker et al., PRL 87 (2001)
L. Reina et al., PRL 87 (2001), PRD65 (2002)

$t\bar{t}$ Higgs production cross sections at the Tevatron Run2

Courtesy of Dave Rainwater; J.Goldstein et al., hep-ph/0006311



→ about 30% more luminosity is needed to reach same sensitivity

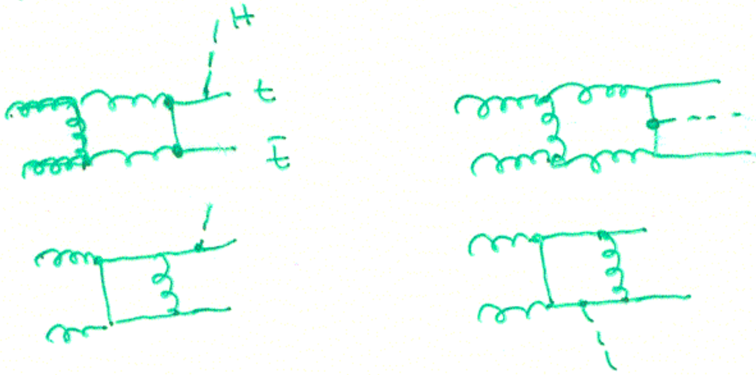
QCD corrections to $t\bar{t}H$ production at the LHC

two groups: W. Beenakker et al., PRL 87 (2001)
S. Dawson et al. (in preparation)

Associated $t\bar{t}H$ production at the LHC is one of the most promising reactions to study both Higgs and top:

- Direct measurement of Top Yukawa Coupling
- Discrimination of SM-like Higgs from MSSM Higgs

Examples of $O(\alpha_s)$ corrections:



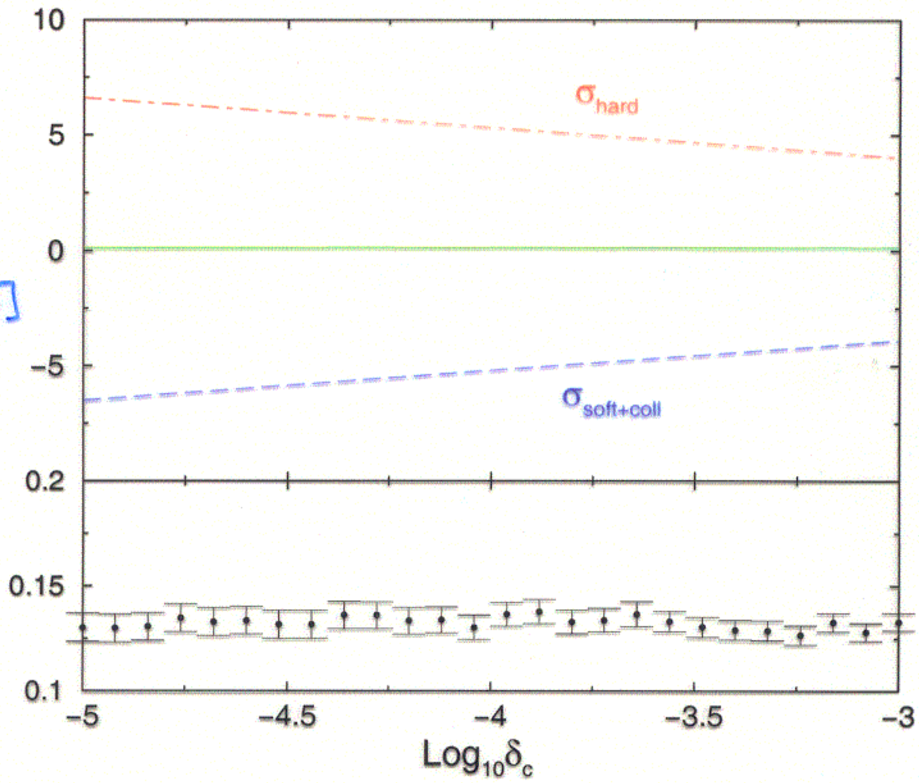
and many more...

QCD corrections to $t\bar{t}H$ production at the LHC:

two groups: W. Beenakker et al., PRL 87 (2001)
S. Dawson et al (in preparation)

Dependence on technical cut-off parameters δ_c and δ_s of the phase space slicing method cancels in σ_{NLO}:

σ_{real} [pb]
(only gg)



preliminary!

$\sigma_{NLO}^{t\bar{t}H}$ at the LHC (14 TeV):

S. Dawson et al. (in preparation)

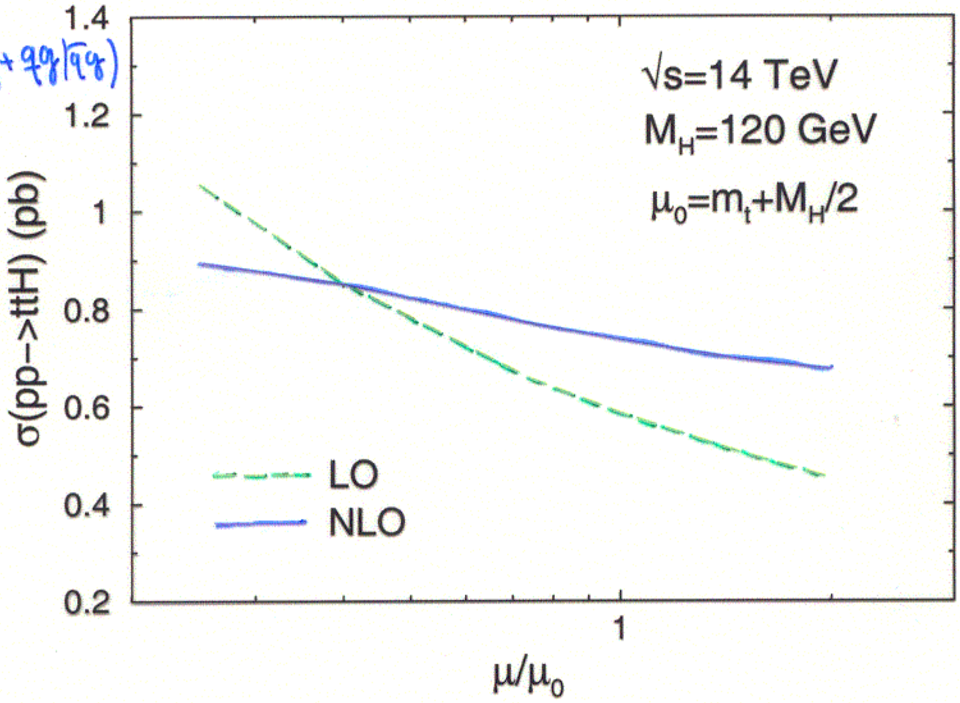
- strongly reduced scale dependence
- QCD corrections enhance σ_{LO} over a wide range of μ!

QCD corrections to $t\bar{t}H$ production at the LHC

Main Result

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

$\sigma_{NLO/LO}(gg + q\bar{q} + qg/\bar{q}g)$



preliminary!
(low statistics)
~ 10% stat. uncert.

S.Dawson, L.Orr, L.Reina, D.W.(in preparation)

~~see also~~ W.Beenakker et al., Phys.Rev.Lett.87 (2001) : $K = 1.2 - 1.4$

$m_t + \frac{M_H}{2} < \mu < 2m_t + M_H$

$M_H = 120\,GeV$

Summary

- $t\bar{t}H$ is a very interesting production mode at present and future colliders:
  - discover/confirm the Higgs
  - measurement of Top Yukawa coupling
  - SM? New Physics?
- It is crucial to know the impact of QCD corrections.
- $\sigma(p\bar{p} \to t\bar{t}H)$ at $\mathcal{O}(\alpha_s^3)$ has been calculated independently by two groups:

  S.Dawson, L.Reina, D.W., Phys.Rev.Lett.87 (2001), Phys.Rev.D65 (2002) and W.Beenakker et al., Phys.Rev.Lett.87 (2001)

  - strongly reduced scale dependence
  - $K = \frac{\sigma_{NLO}}{\sigma_{LO}} = 0.7 - 1$ (Tevatron, 2TeV) $m_t < \mu < 2m_t + M_H$, $M_H = 120$ GeV
- $\sigma(pp \to t\bar{t}H)$ at $\mathcal{O}(\alpha_s^3)$: W. Beenakker et al. PRL87 (2001) S. Dawson et al. (in prep.)
  - strongly reduced μ dep.
  - $K = 1.2 - 1.4$ $m_t + \frac{M_H}{2} < \mu < 2m_t + M_H$, $M_H = 120$ GeV (Beenakker et al.)