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Higgs Radiation off Heavy Quarks at Future Colliders

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III Outlook on $b\bar{b}H$ production at hadron colliders

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Introduction

- To establish the SM Higgs mechanism we have to
  - discover the Higgs boson(s),
  - establish the mass generation: $g_{XX\phi} \sim m_X$,
  - and reconstruct the Higgs potential.

- Current experimental limits on M_H (95% C.L.):
  - $e^+e^- \not\longrightarrow ZH$ at LEP2
    $\Rightarrow M_H > 114.1$ GeV (LEPHIGGS '01).
  - Fit to electroweak precision data
    $\Rightarrow M_H < 196$ GeV (LEPEWWG '01).

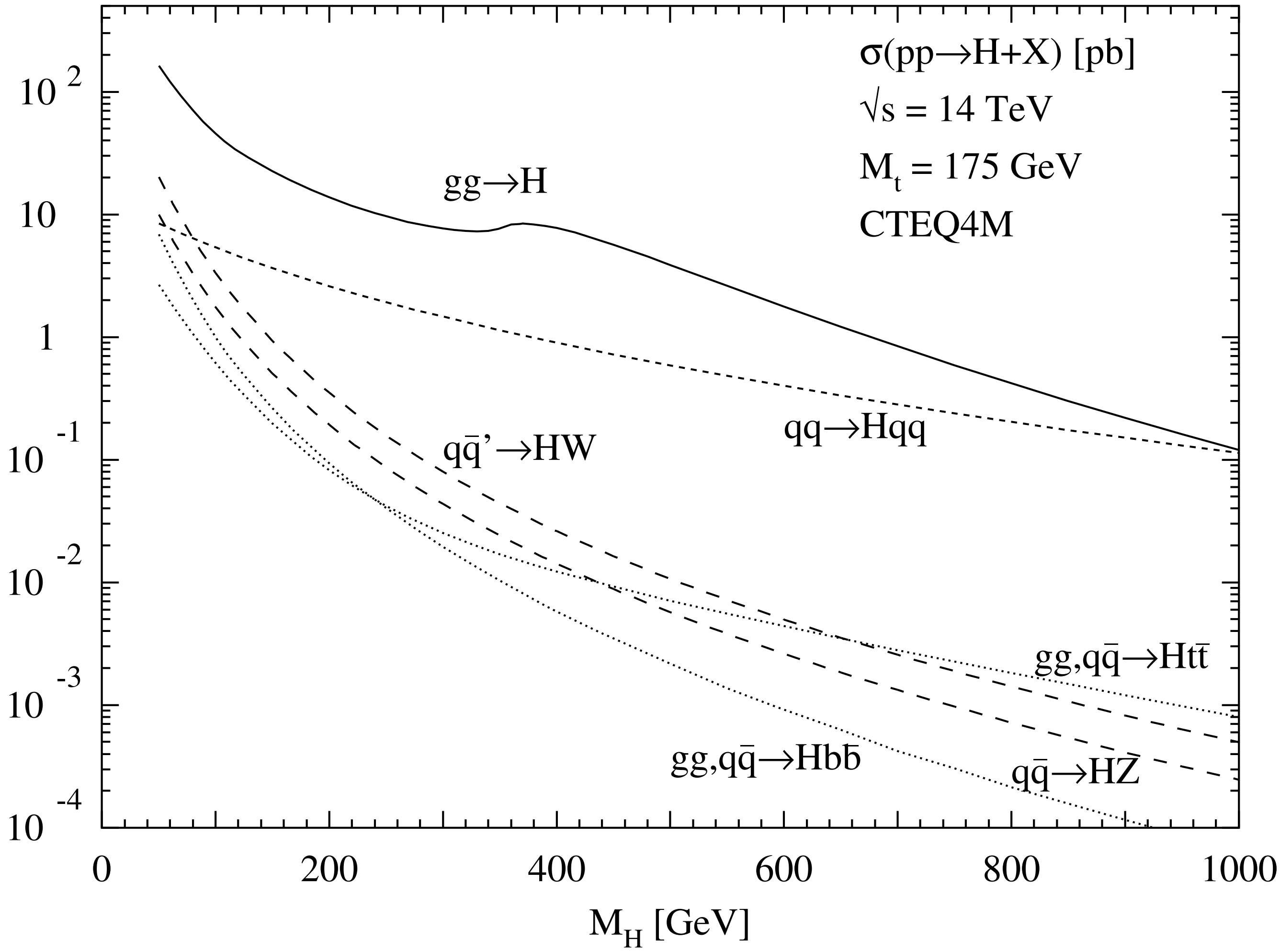
- Evidence for light Higgs boson at LEP2?

  2.1σ excess over background
  with maximum likelihood at $M_H = 115.6$ GeV
  (LEPHIGGS '01).

Higgs Boson Searches at the LHC

- Production cross section:

(Spira et al.)



⇒ $\sigma \approx 20$ pb (dominated by gluon fusion)

↪ ≈ 600000 Higgs-events/year

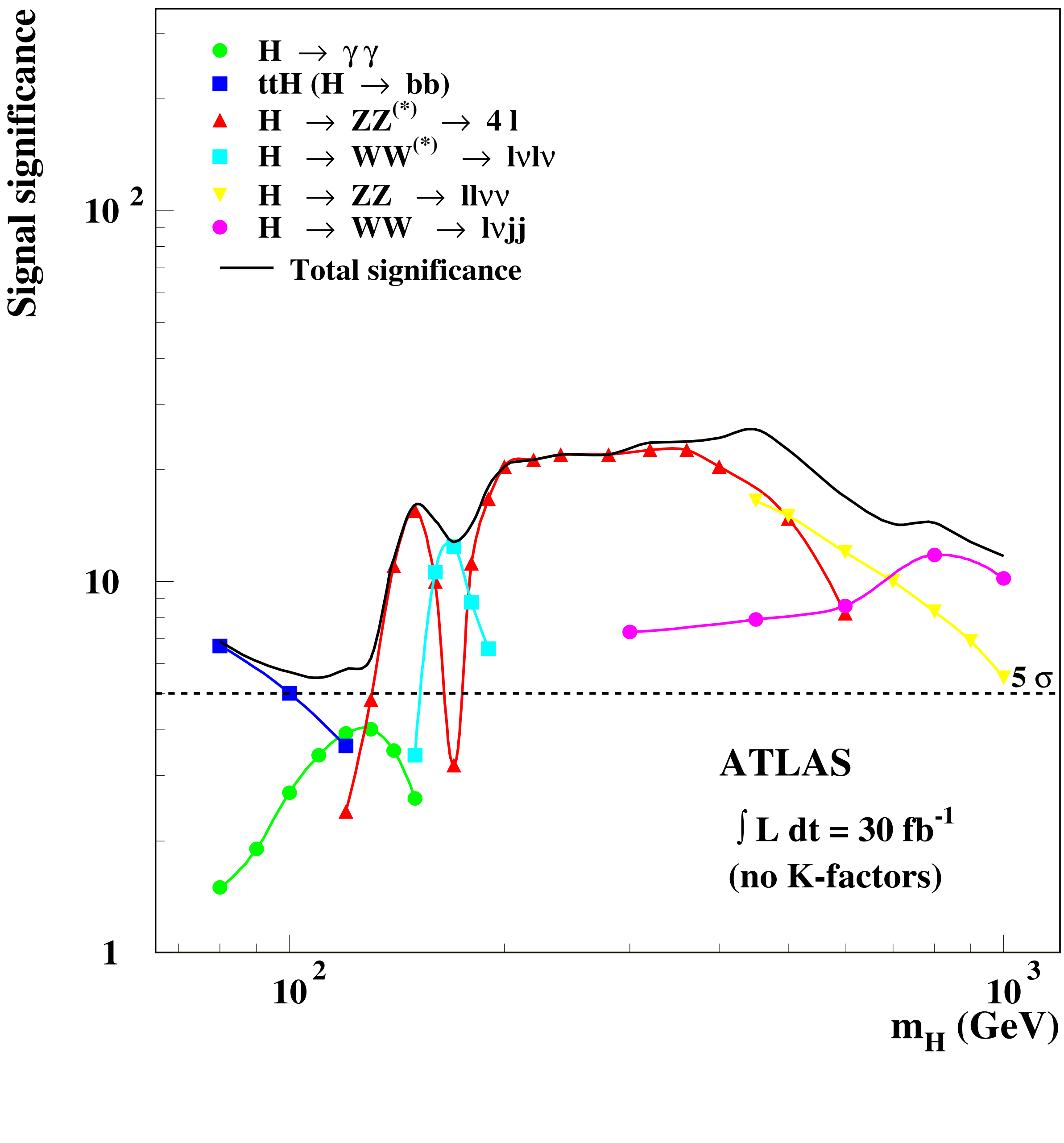
(initial LHC luminosity $\int \mathcal{L} = 30\ \text{fb}^{-1}$)

But: large QCD backgrounds: $\sigma_{b\bar{b}} \approx 10^3\ \mu$b

⇒ consider more distinctive final states.

For $m_H \lesssim 130$ GeV:

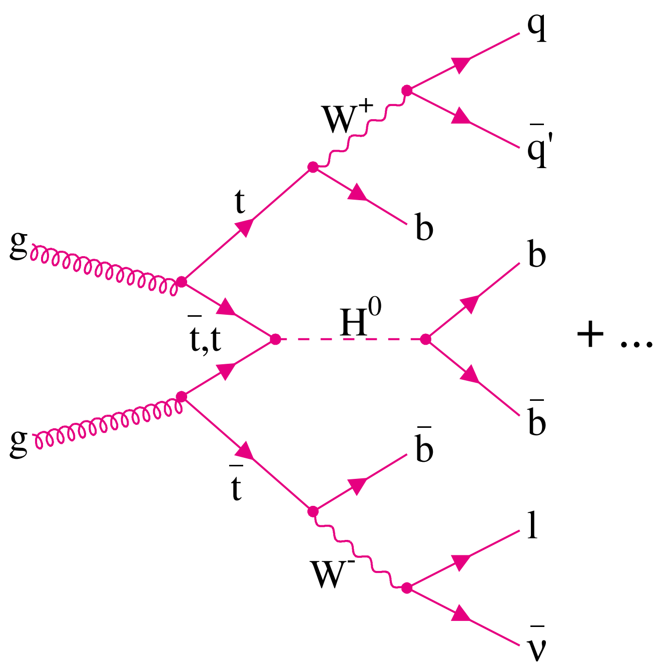
use $H \to \gamma\gamma$ and $t\bar{t}H$ associated production.



$t\bar{t}H$ associated production

- distinctive final state:

  $pp \to t(\to W^+b)\ \bar{t}(\to W^-\bar{b})\ H(\to b\bar{b})$



$\rightarrow$ important contribution to 5σ discovery for $M_H \lesssim 130$ GeV

$\rightarrow$ Higgs mass reconstruction with $\delta M_H/M_H \approx 4\%$

(Drollinger, Müller, Denegri; Pickford)

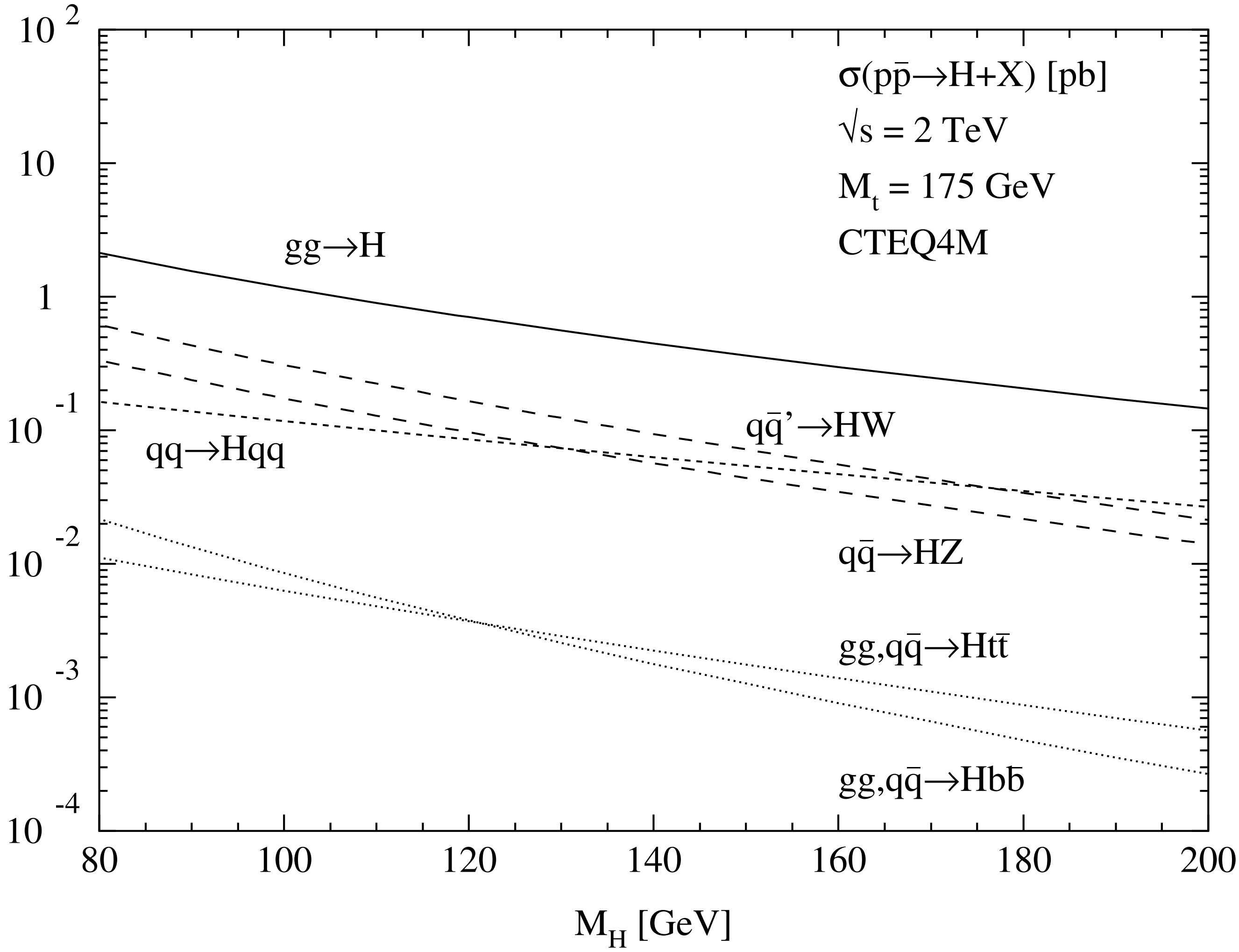
- cross section $\propto g_{ttH}^2$

$\Rightarrow$ direct measurement of top Yukawa coupling

$\delta g_{ttH}/g_{ttH} \approx 15\%$ (exp.) (Drollinger, Müller, Denegri)

What about the Tevatron?

Production cross section



– cross section by factor $\approx 10^2 - 10^3$ smaller than at LHC

– combine many channels for Higgs search

– need $\int\mathcal{L} \gtrsim 20\ \mathrm{fb}^{-1}$ to discover Higgs with $M_H = 120$ GeV

- $t\bar{t}H$ associated production

  only few events ($\sigma \approx 5$fb), but low background

  $\rightarrow$ can reduce $\int\mathcal{L}$ need for Higgs discovery by $\approx 15 - 20\%$
  (Goldstein et al.; Incandela)

$pp/p\bar{p} \to t\bar{t}H$ Cross Section Prediction

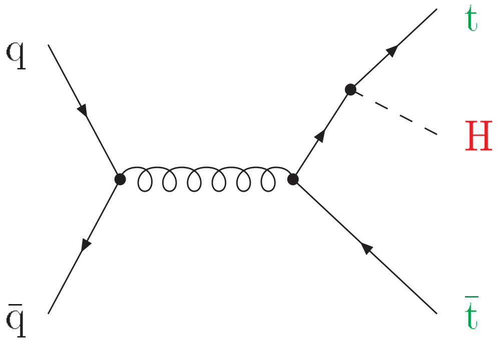
- Precise theoretical predictions essential to

– reliably estimate significance of discovery/exclusion

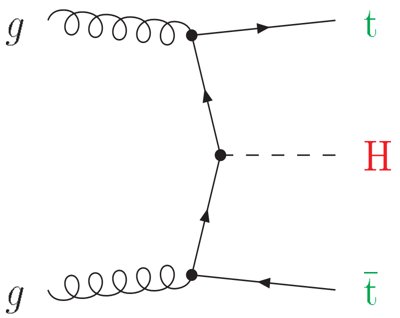
– obtain measurement of top Yukawa coupling

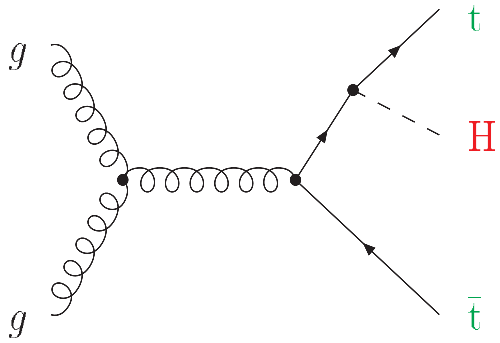
- Production mechanism at leading order:

through $q\bar{q}$ annihilation



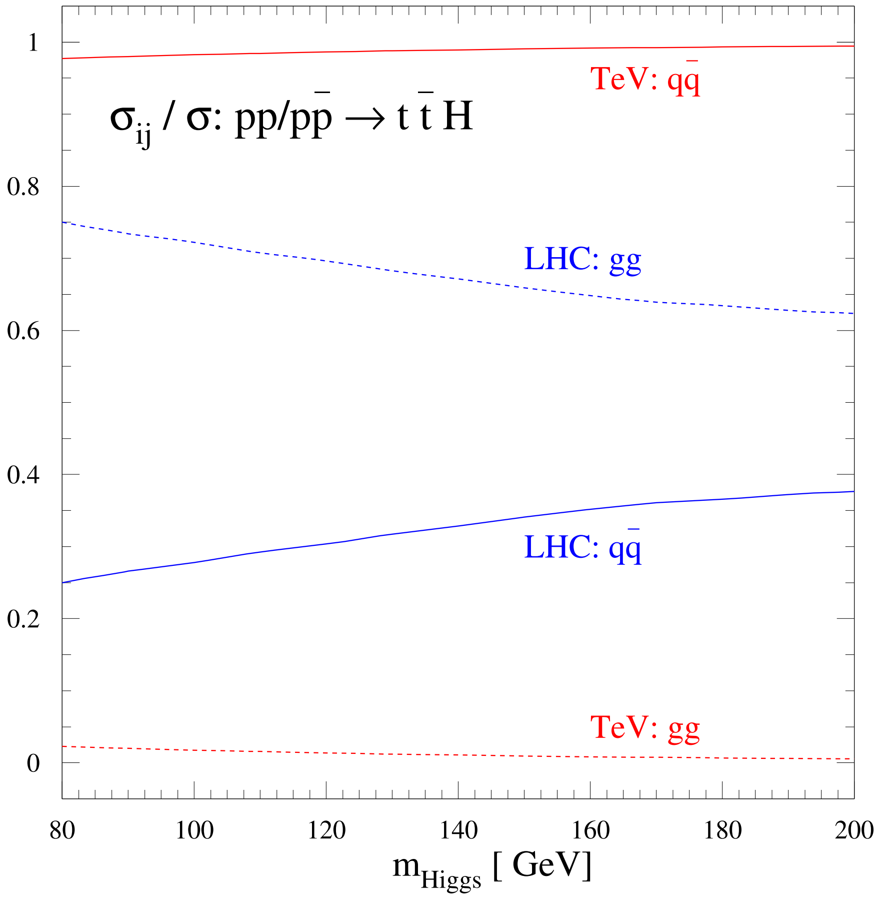
and through gg fusion





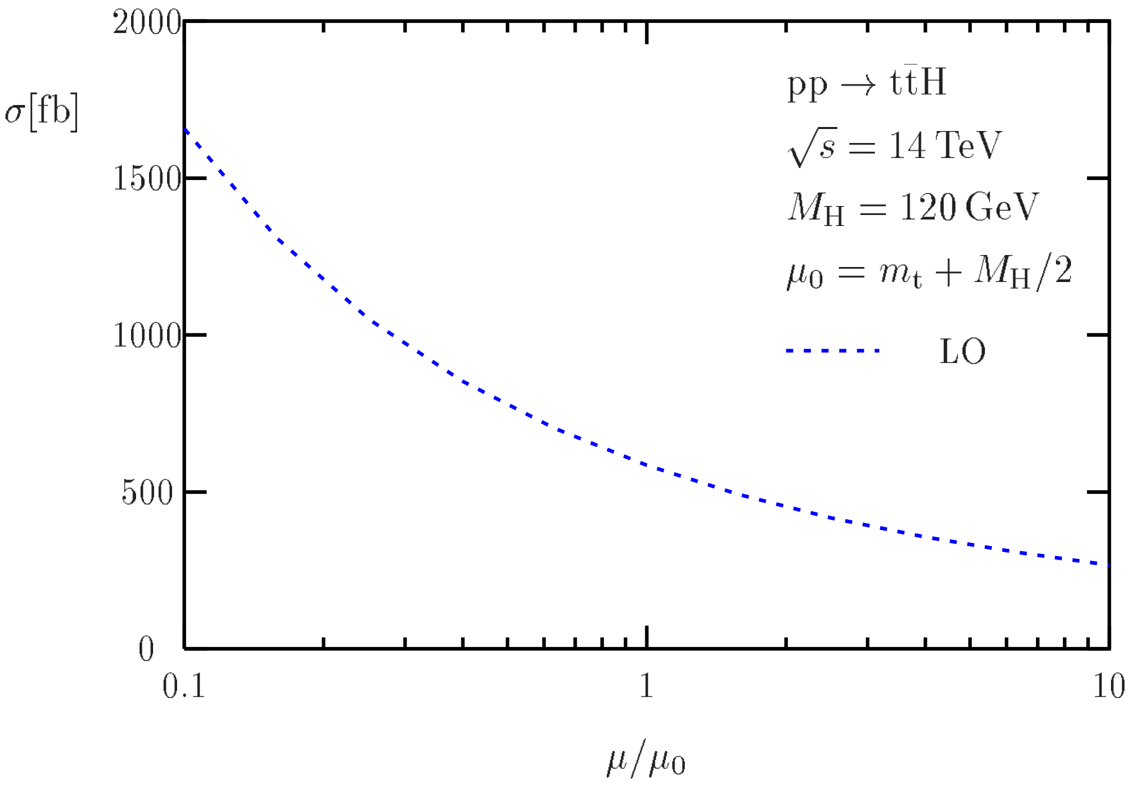
(Kunszt '84; Dicus, Willenbrock '89; Gunion '91; Marciano, Paige '91)

- relative contribution of $q\bar{q}/gg$ channels



$$\left.\begin{array}{l}\text{Tevatron}\\ \text{LHC}\end{array}\right\}\ \text{cross section dominated by}\ \left\{\begin{array}{l} q\bar{q}\ \text{annihilation}\\ gg\ \text{fusion}\end{array}\right.$$

- Scale dependence of LO cross section



$\Rightarrow$ NLO calculation needed

- Recent progress:

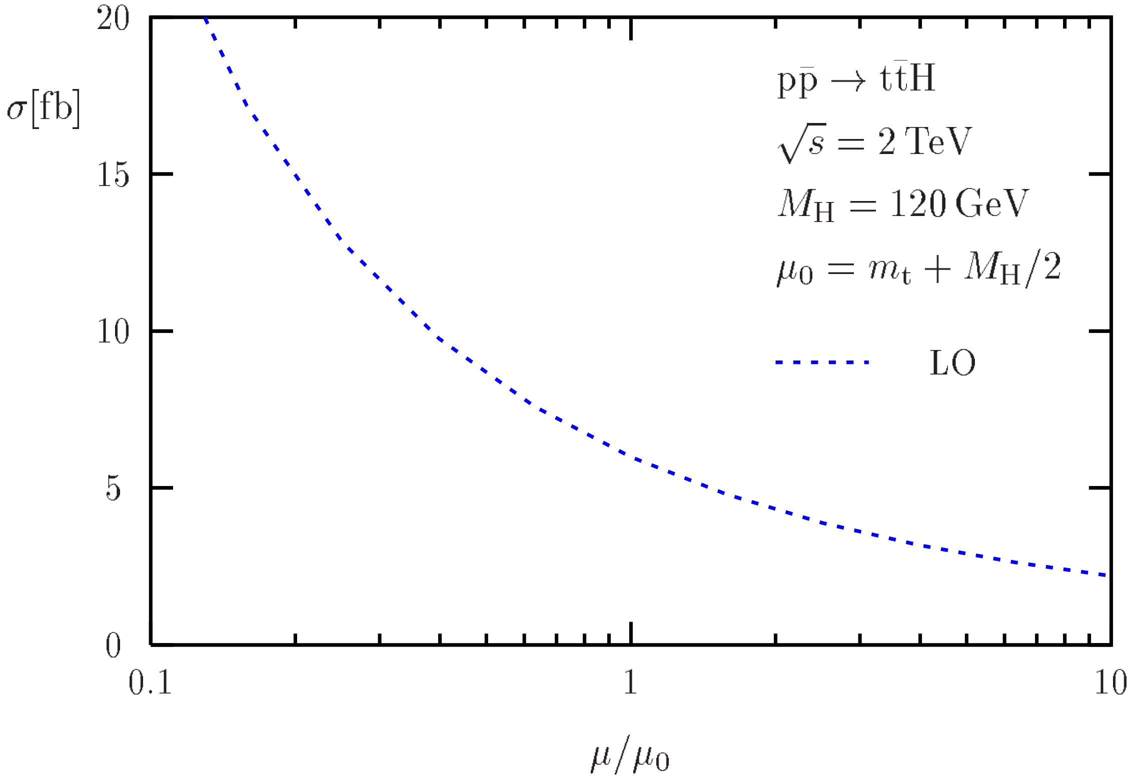
  Beenakker, Dittmaier, MK, Plümper, Spira, Zerwas:
  $\mathcal{O}(\alpha_s)$ QCD corrections to $pp/p\bar{p} \to t\bar{t}H$ at the Tevatron and at the LHC (including $q\bar{q}$ and gg channels).

  Reina, Dawson, Wackeroth:
  $\mathcal{O}(\alpha_s)$ QCD corrections to $pp/p\bar{p} \to t\bar{t}H$ at the Tevatron ($q\bar{q}$ only).

Exact results in qualitative agreement with estimate of NLO corrections for $M_H^2 \ll m_t^2 \ll \langle\sqrt{s}\rangle^2$ in "equivalent Higgs approximation" (Dawson and Reina '98)

• Scale dependence of LO cross section

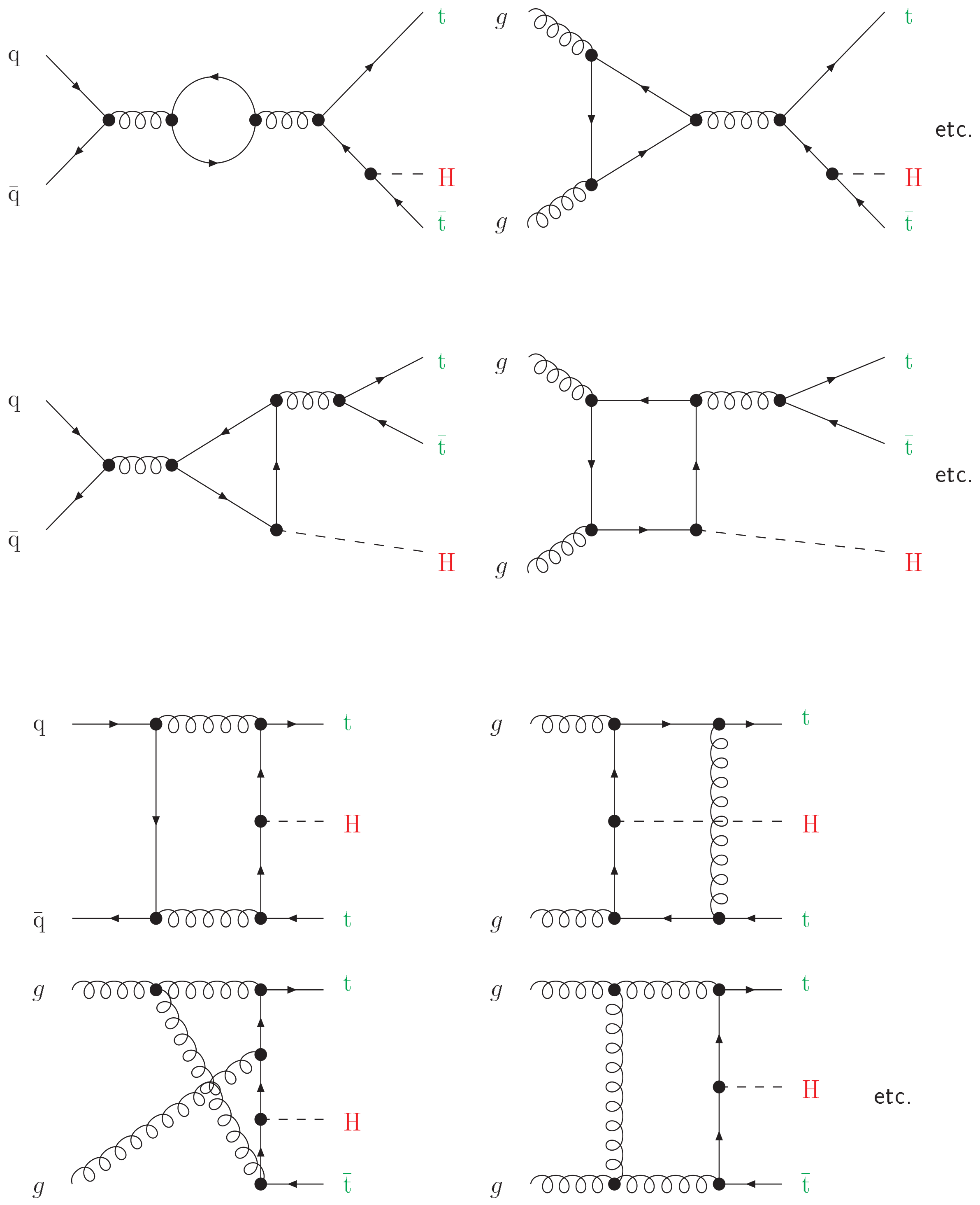
at the Tevatron



NLO corrections to $q\bar{q}/gg \to t\bar{t}H$

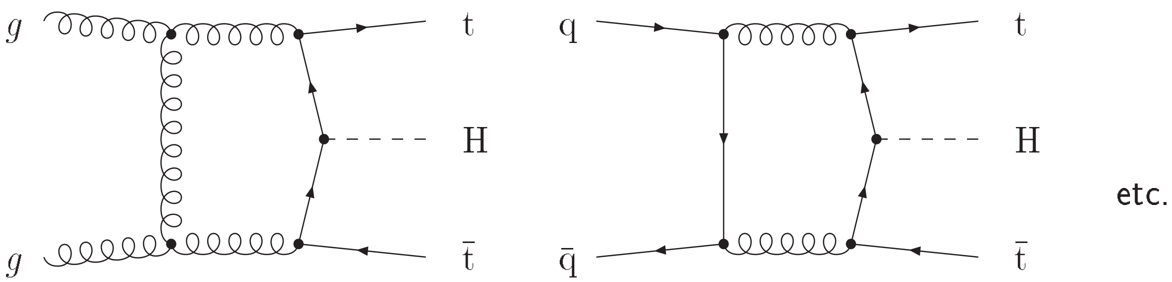
- Virtual corrections

generic set of Feynman diagrams



Challenges in the virtual corrections

Pentagon diagrams



$\rightarrow$ one-loop integrals of the form

$$E_{\mu\nu\cdots} = \frac{(2\pi\mu)^{4-D}}{i\pi^2} \int d^D q \frac{q_\mu q_\nu \cdots}{[(q+p_1)^2 - m_1^2] \cdots [(q+p_5)^2 - m_5^2]}$$

– determine singularity structure $E_{\text{sing}}^{(D)}$ in D dimensions
  $\rightarrow$ three-point subintegrals

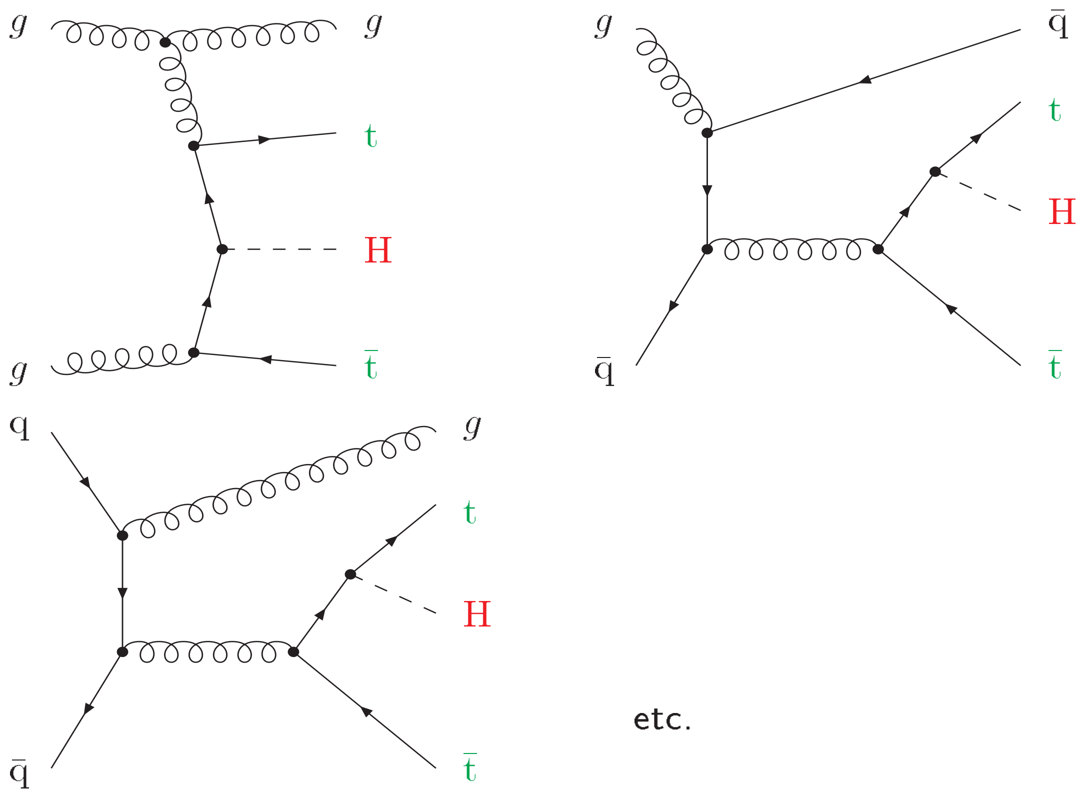
– translate (finite) difference $E^{(D)} - E_{\text{sing}}^{(D)}$ into mass regularisation
  $\rightarrow$ can be decomposed into four-point subintegrals

$\Rightarrow$ $E^{(D)} = E_{\text{sing}}^{(D)} + \left[E^{(\text{mass}, D=4)} - E_{\text{sing}}^{(\text{mass}, D=4)} \right]$

expressed in terms of three- and four-point functions

- Real corrections

generic set of Feynman diagrams



Challenges

– evaluation of complicated matrix elements

→ application of conventional trace techniques and use of helicity amplitudes (`Madgraph`, Stelzer, Long)

– extraction of soft and collinear divergences

→ use dipole subtraction formalism

(additional check: phase space slicing for $q\bar{q}$ channel)

Dipole subtraction formalism:

(Catani, Seymour '96; Dittmaier '99, Roth '99;
Phaf, Weinzierl '01; Catani, Dittmaier, Seymour, Trócsányi '01)

$\rightarrow$ process-independent treatment of singularities
in real NLO corrections

idea: NLO correction to process with m partons

$$\sigma^{\rm NLO} = \underbrace{\int_{m+1} \left[d\sigma^{\rm real} - d\sigma^{\rm sub} \right]}_{\text{finite}} + \underbrace{\int_{m} \left[d\sigma^{\rm virtual} + d\bar{\sigma}_1^{\rm sub} \right]}_{\text{finite}}$$

$$+ \int_0^1 dx \underbrace{\int_m \left[d\sigma^{\rm fact}(x) + \Big(d\bar{\sigma}^{\rm sub}(x) \Big)_+ \right]}_{\text{finite}}$$

conditions on $d\sigma^{\rm sub}$:

- sum rule:

$$- \int_{m+1} d\sigma^{\rm sub} + \int_m d\bar{\sigma}_1^{\rm sub} + \int_0^1 dx \int_m \Big(d\bar{\sigma}^{\rm sub}(x) \Big)_+ = 0$$

- asymptotics:

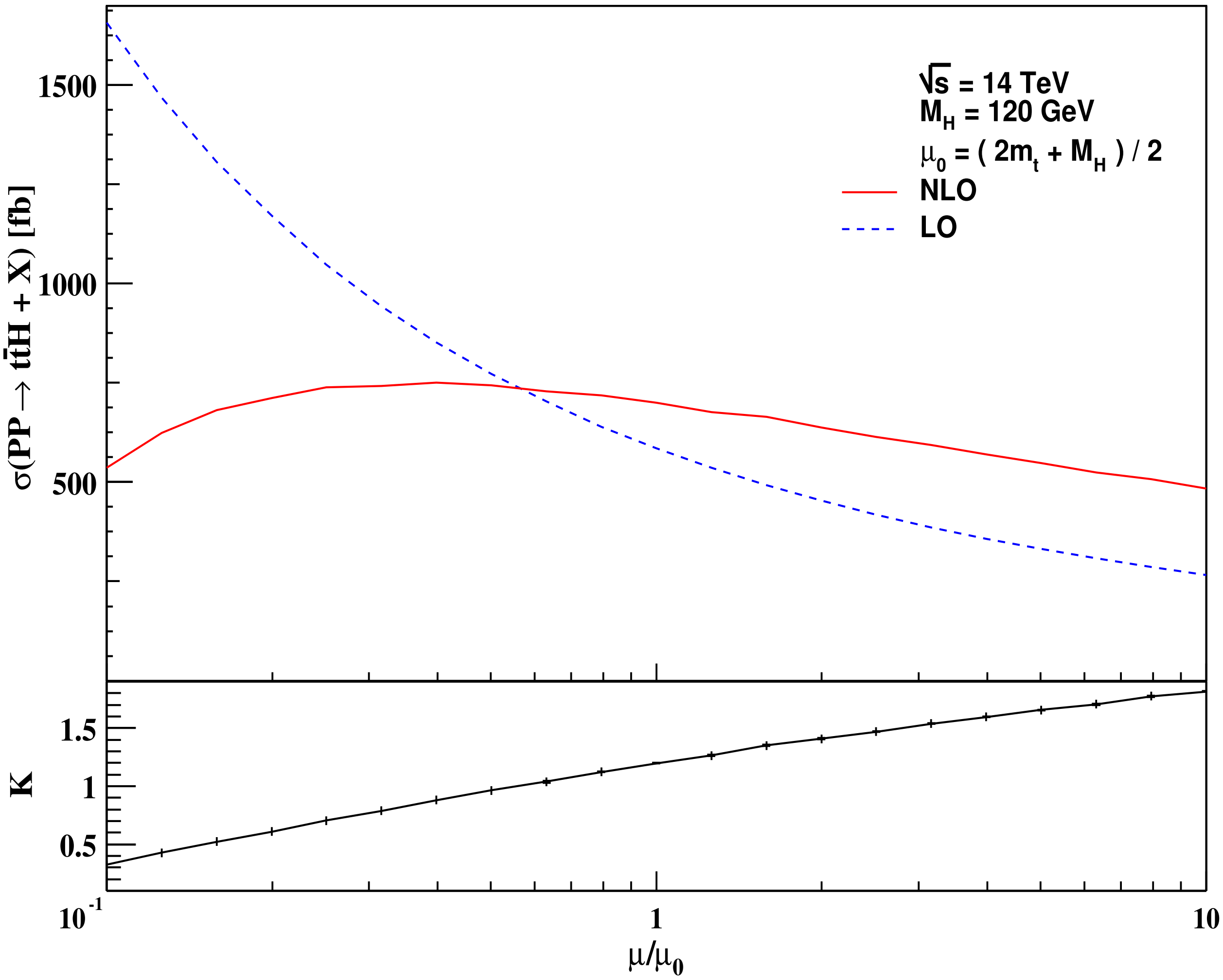
$\sigma^{\rm sub} \sim \sigma^{\rm real}$ in all collinear/IR regions

Results for $pp/p\bar{p} \to t\bar{t}H$ cross section

- scale dependence at NLO
- NLO cross sections at the Tevatron and the LHC
- Higgs transverse momentum distribution
- top-quark transverse momentum distribution

Scale dependence at NLO

LHC:

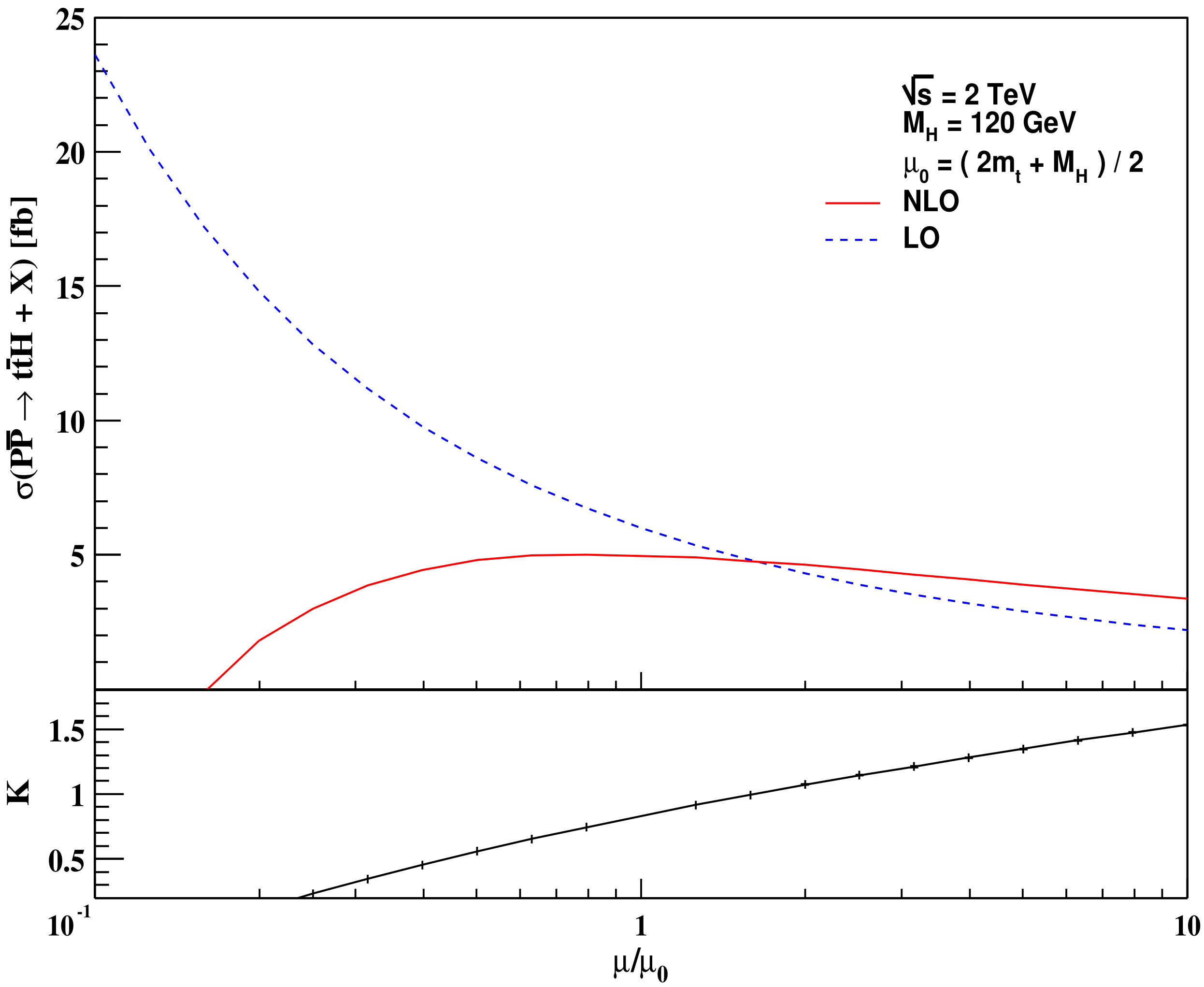


Scale variation within $\mu_0/3 \lesssim \mu \lesssim 3\mu_0$:

$$\frac{\delta\sigma_{\rm LO}}{\sigma_{\rm LO}} \approx 2 - 3 \qquad \frac{\delta\sigma_{\rm NLO}}{\sigma_{\rm NLO}} \approx 20\%$$

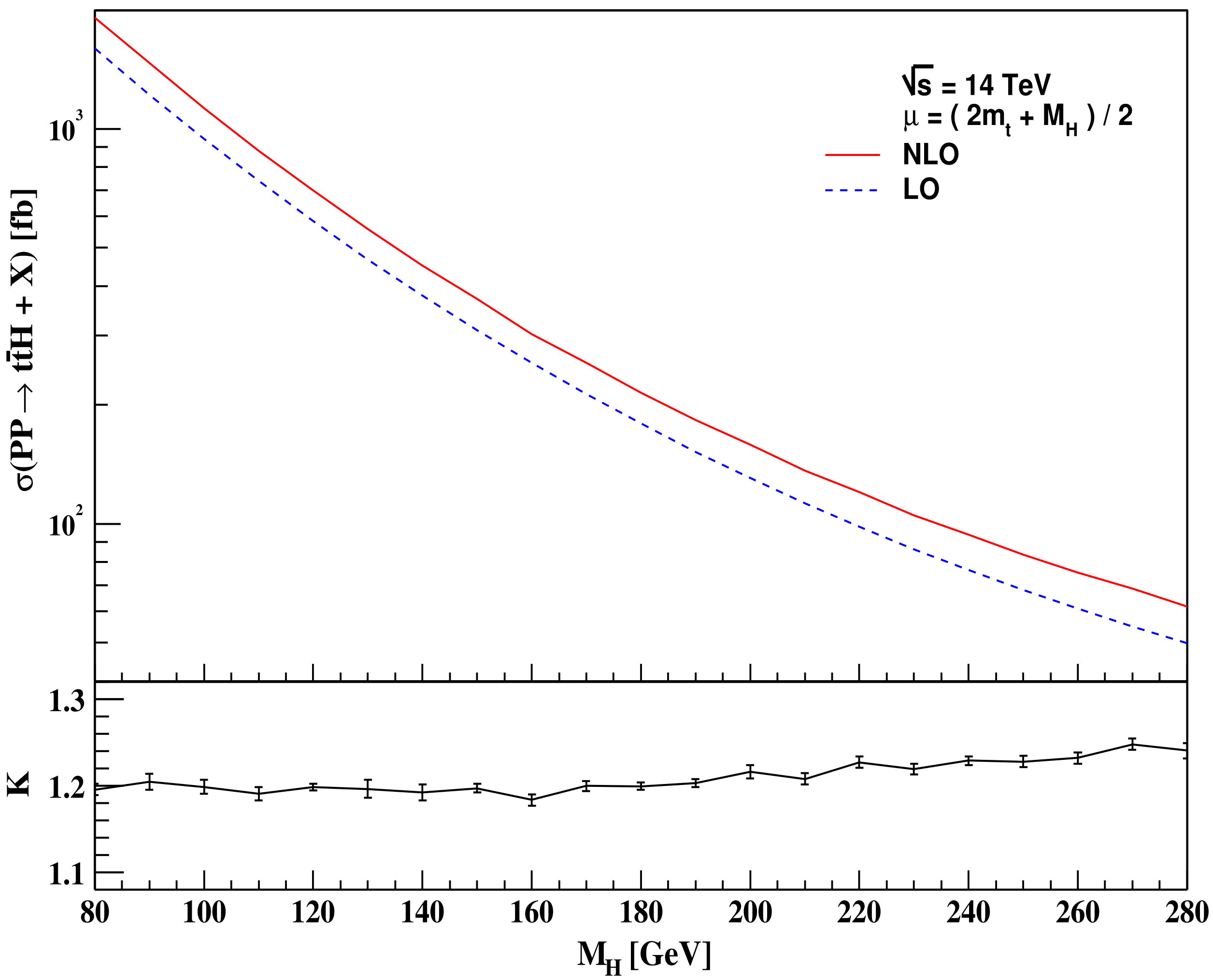
Scale dependence at NLO

Tevatron:



NLO cross section at the LHC

LHC:

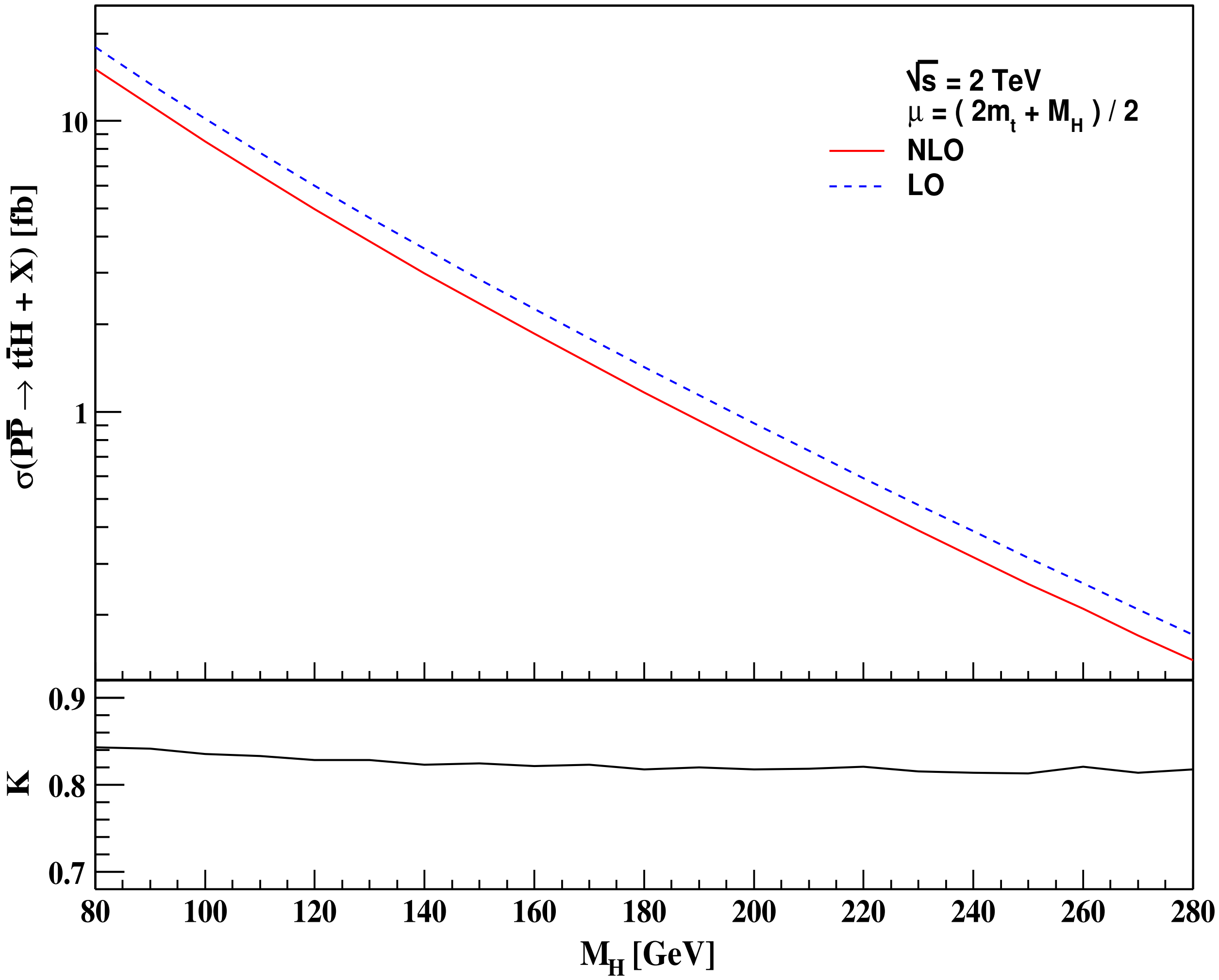


Relative correction for $\mu = \mu_0 = (2m_t + M_H)/2$:

$$K = \frac{\sigma_{\rm NLO}}{\sigma_{LO}} \approx 1.2$$

NLO cross section at the Tevatron

Tevatron:

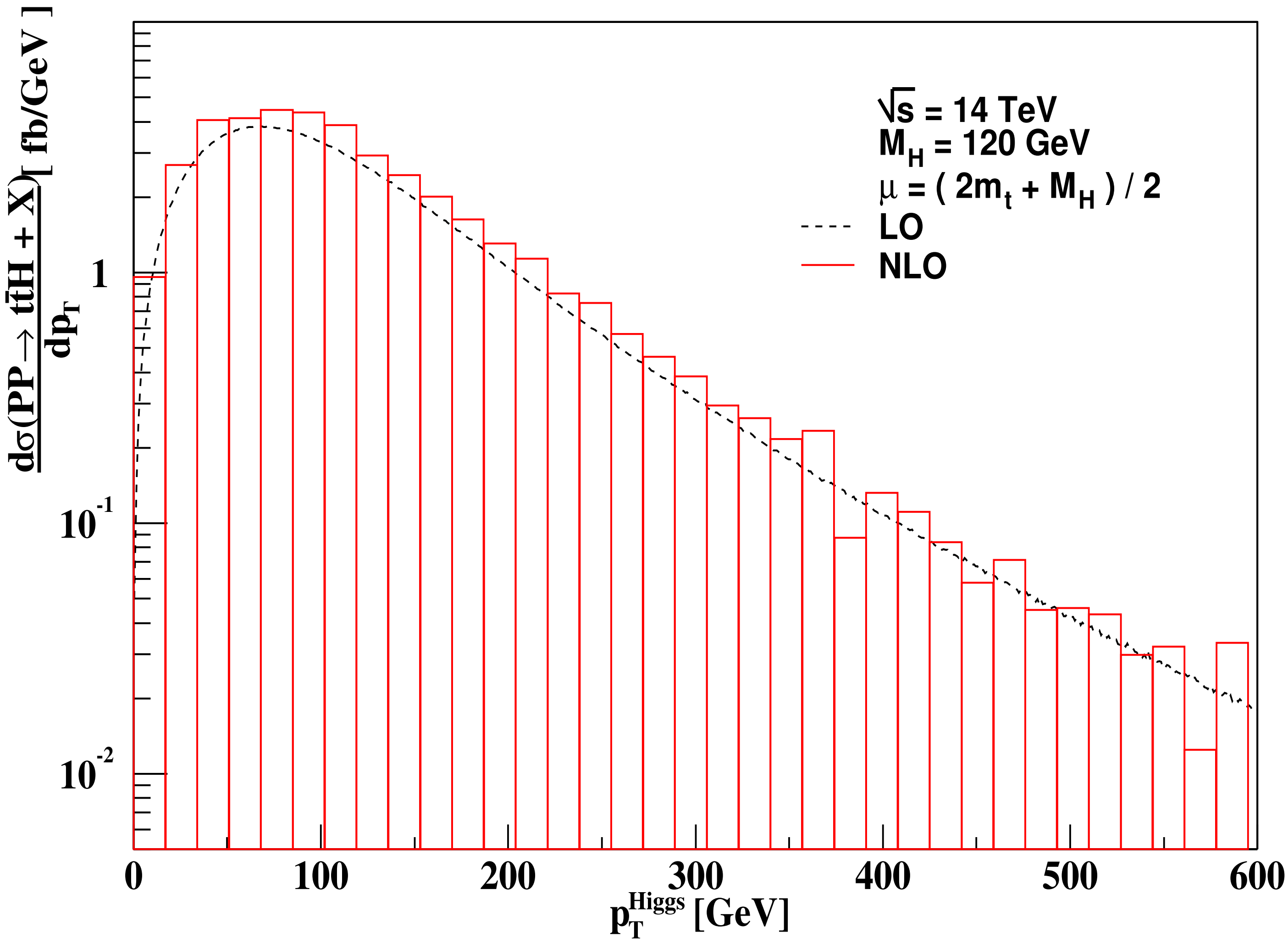


Relative correction for $\mu = \mu_0 = (2m_t + M_H)/2$:

$$K = \frac{\sigma_{\rm NLO}}{\sigma_{LO}} \approx 0.8$$

Higgs transverse momentum distribution

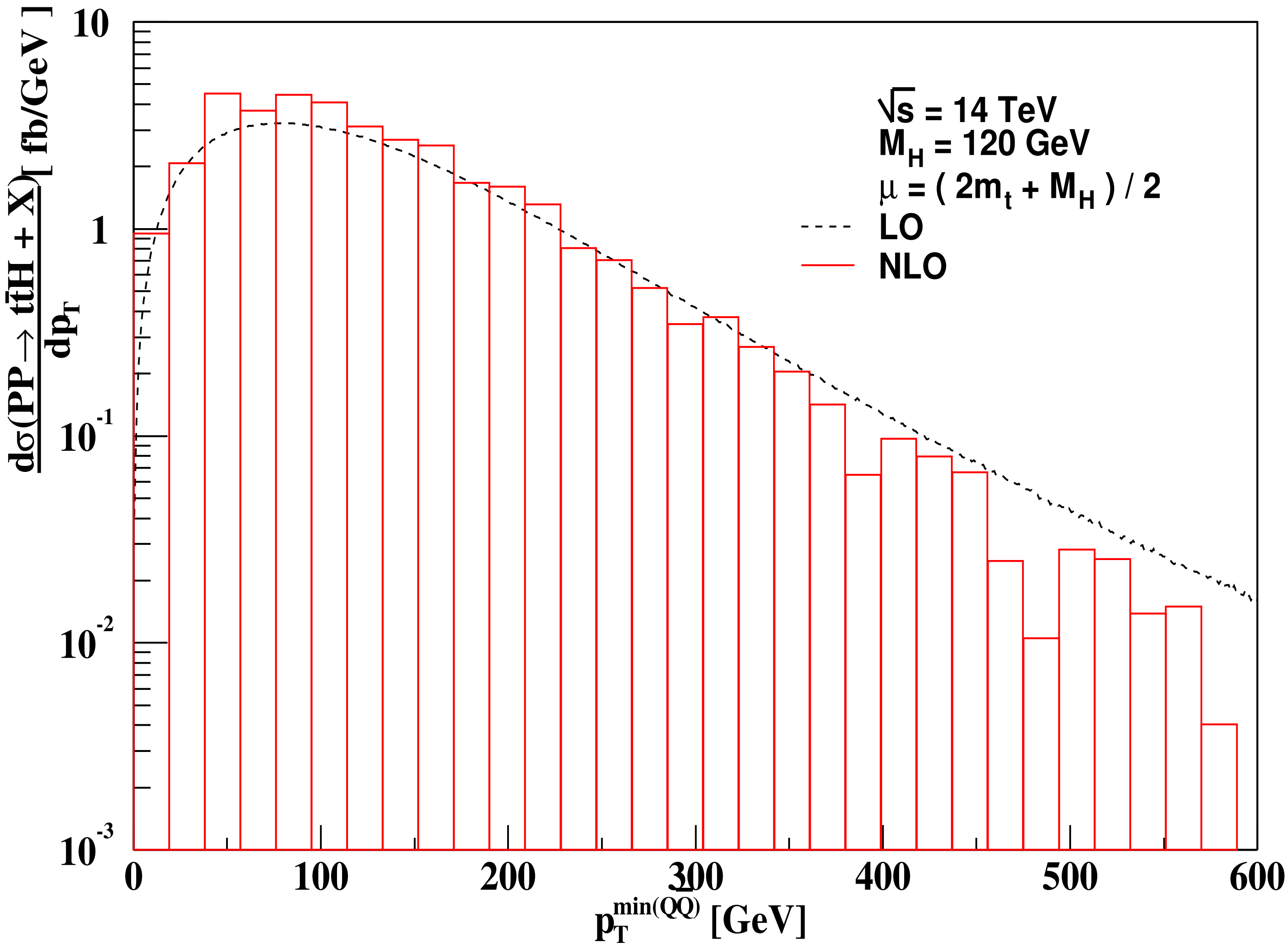
LHC:



K-factor rescaling of LO distribution is good approximation

Top-quark transverse momentum distribution

LHC:

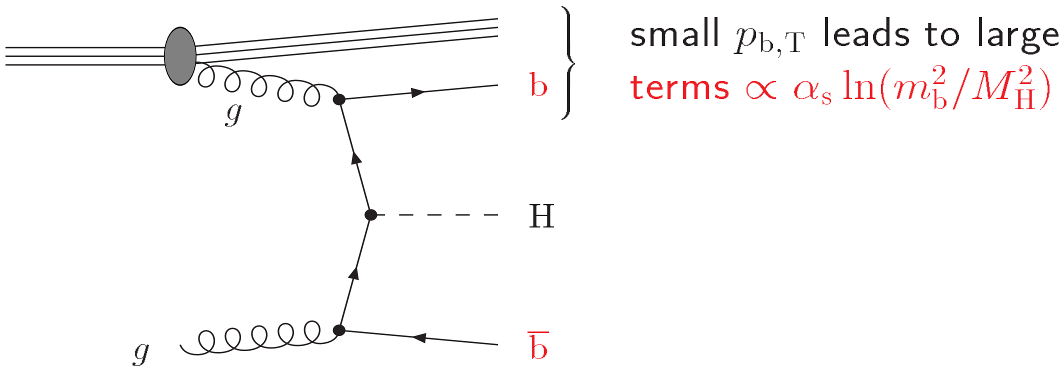


Shapes of NLO and LO distributions are different

Outlook: $b\bar{b}h$ Production at Hadron Colliders

- $b\bar{b}h$ coupling enhanced in SUSY models for large $\tan\beta$
  $\rightarrow pp/p\bar{p} \rightarrow b\bar{b}h$ is potential discovery channel

Problem:



Summation of $\alpha_s \ln(m_b^2/M_H^2)$ terms by introducing
b-quark density $b(x,\mu)$ $\rightarrow$ LO process: $b\bar{b} \rightarrow H$
(Barnett, Haber, Soper; Dicus, Stelzer, Sullivan, Willenbrock)

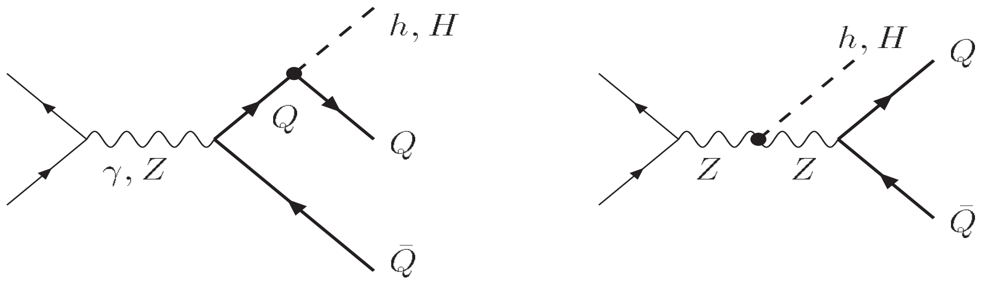
Shortcomings: b quark mass neglected
intrinsic p_T of b quarks neglected
$\rightarrow$ how to deal with tagged b quarks?

Work in progress:

- estimate size of $\alpha_s \ln(m_b^2/M_H^2)$ terms
- study p_T distribution for b quarks in $gg/q\bar{q} \rightarrow b\bar{b}H$
- match $b\bar{b} \rightarrow H$ and $gg/q\bar{q} \rightarrow b\bar{b}H$ processes at NLO
- ...

$t\bar{t}H$ Production at a Future e^+e^- Collider

- $e^+e^- \to t\bar{t}H$



detailed experimental simulation

(Juste, Merino; Baer, Dawson, Reina; Moretti)

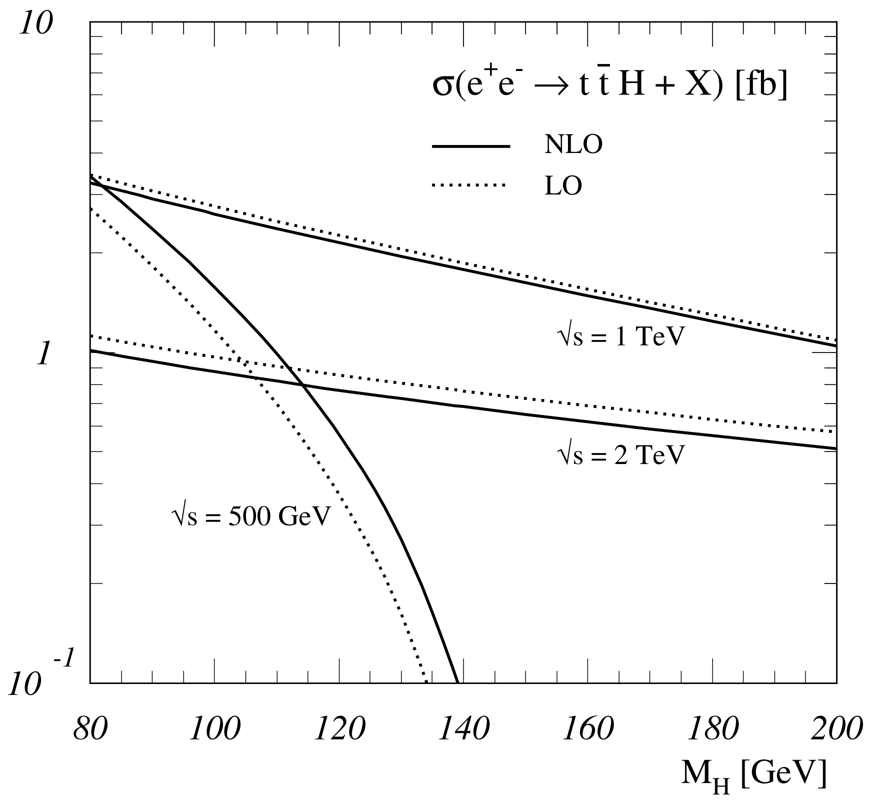
$\to$ $\Delta g_{ttH} \lesssim 5\%$

($\sqrt{s} = 800$ GeV, $m_H = 120$ GeV, $\int \mathcal{L} = 1000$ fb^{-1})

$\Rightarrow$ need for precise theoretical prediction

- NLO corrections known in SM and MSSM

(Dittmaier, MK, Liao, Spira, Zerwas; Dawson, Reina)



Summary

- $t\bar{t}H$ production at hadron colliders:
  - discovery channel at the LHC (Tevatron)
  - first measurement of top Yukawa coupling
  - drastically reduced theoretical uncertainty at NLO
- $b\bar{b}H$ production at hadron colliders:
  - discovery channel for SUSY Higgs at large $\tan\beta$
  - theoretical description more involved
  - NLO calculation in progress...
- $t\bar{t}/b\bar{b}H$ production at e^+e^- colliders:
  - precision measurement of Yukawa couplings
  - NLO calculations available in SM and MSSM