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NLO QCD corrections to Higgs production with associated heavy-quark pairs at hadron colliders

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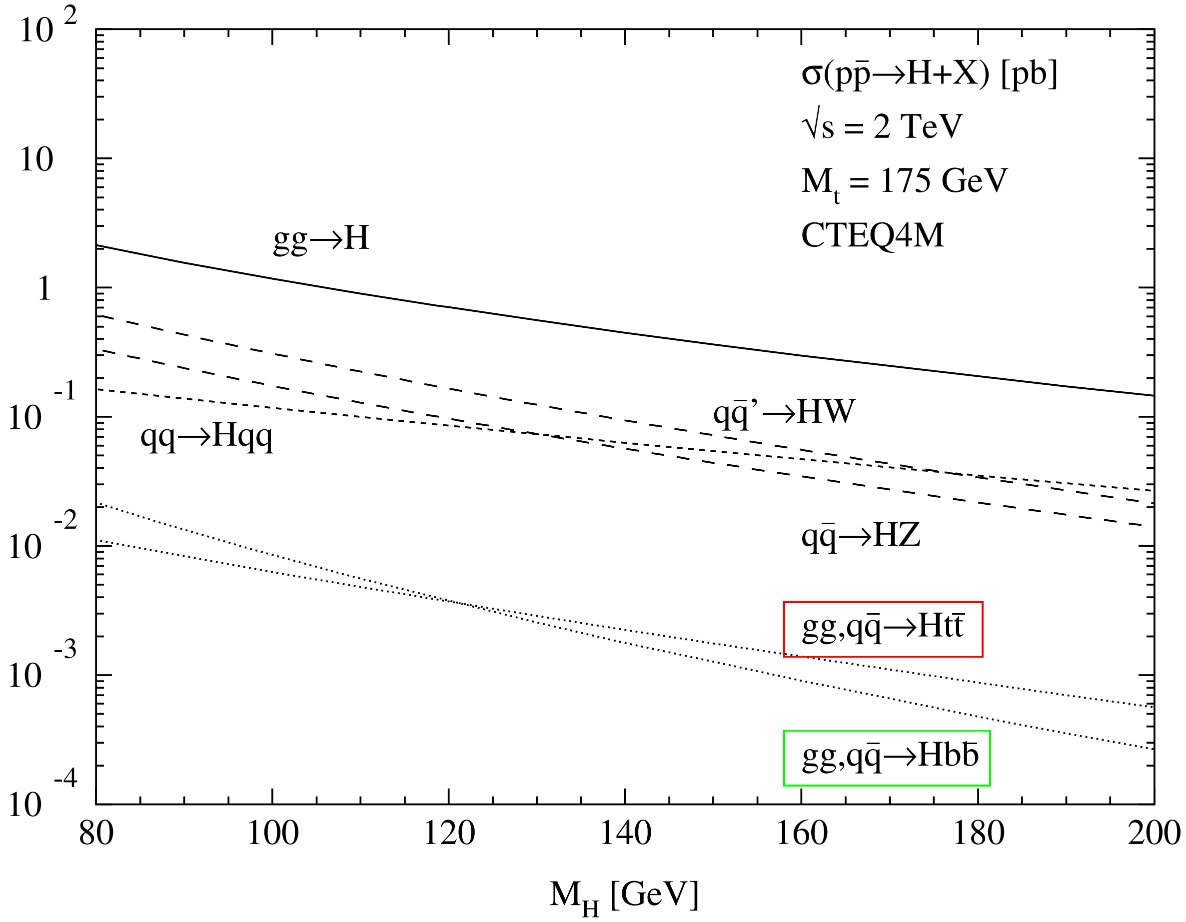
Higgs-boson production at Tevatron

Spira '98



$t\bar{t}H$ production:

- only very few events, but low background

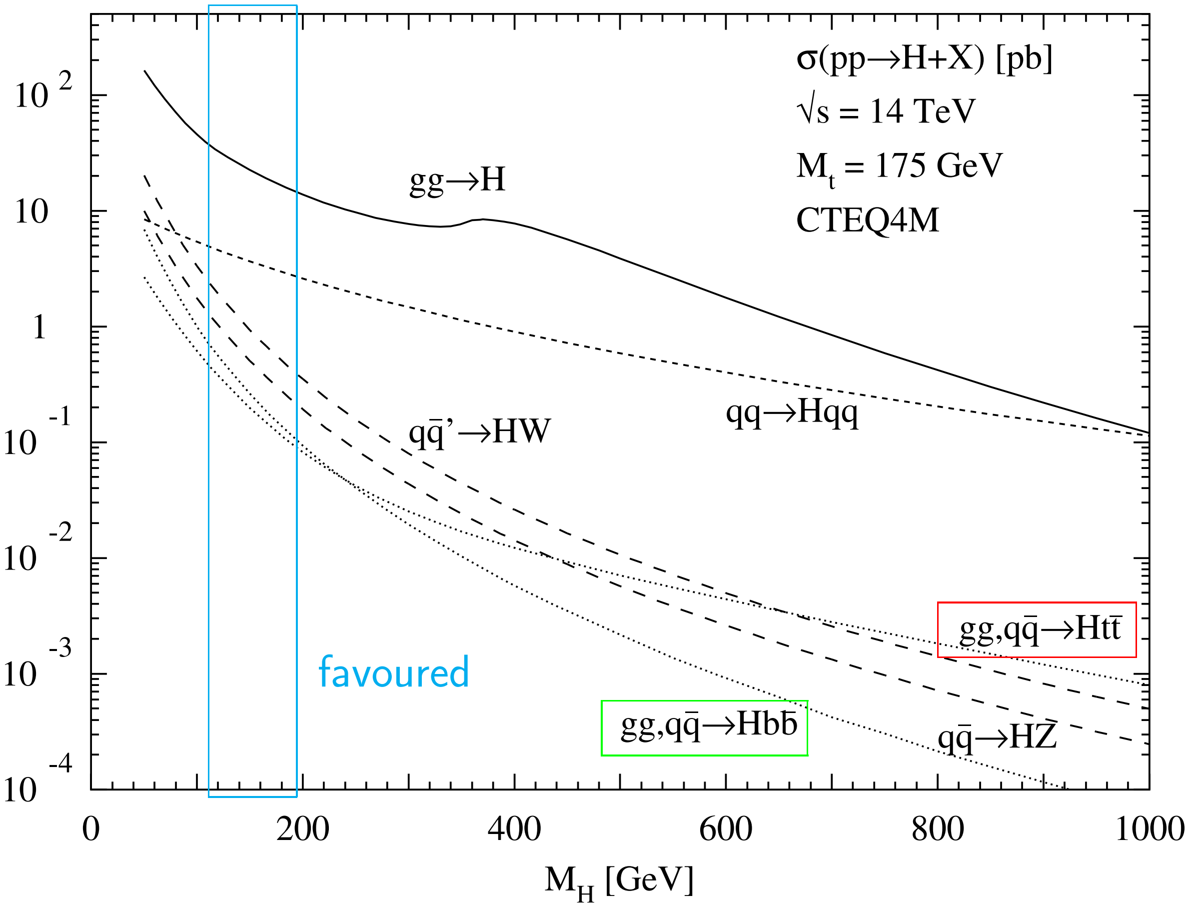
Goldstein, Hill, Incandela
Parke, Rainwater, Stuart '00

$b\bar{b}H$ production:

- enhanced in SUSY models for large $\tan\beta$

Higgs-boson production at the LHC

Spira '98

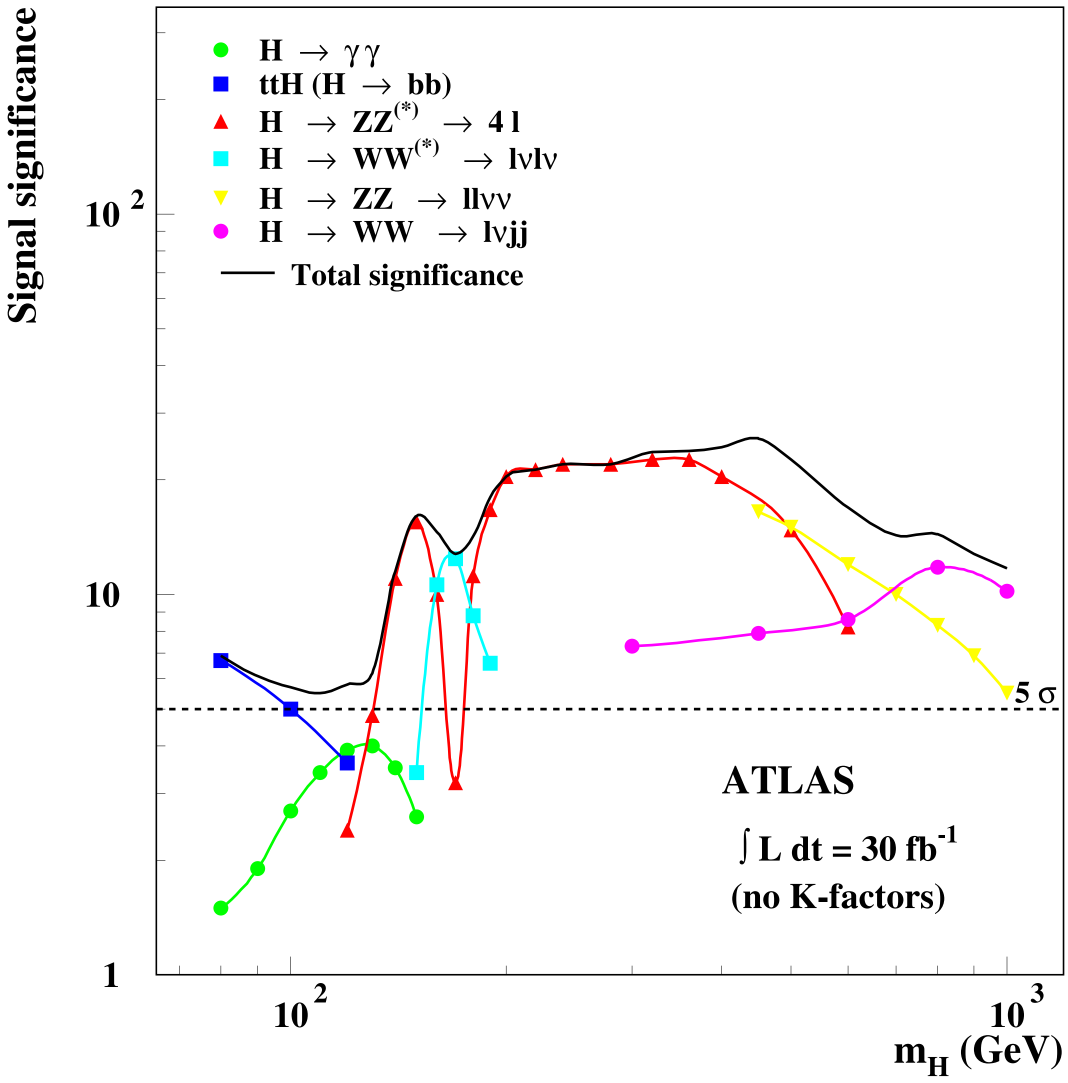


$\mathrm{t\bar{t}H}$, $\mathrm{b\bar{b}H}$ production:

- cross sections by factor $\sim 10^2$–10^3 larger than at Tevatron
- $\mathrm{t\bar{t}H}$ channel represents substantial contribution to 5σ discovery for $M_\mathrm{H} \lesssim 120\,\mathrm{GeV}$
- determination of t and b Yukawa couplings

Significance of Higgs signals for ATLAS:

ATLAS '99

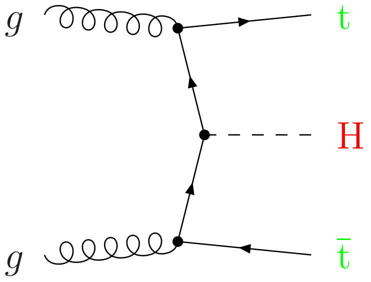


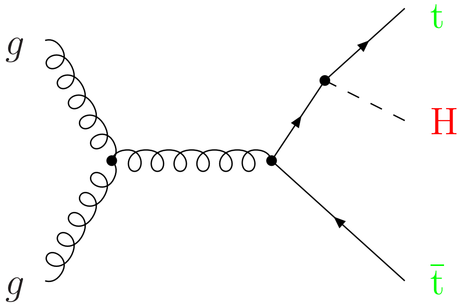
$\Rightarrow$ $\mathrm{t\bar{t}H}$ production very important for small M_{H}

2 $\mathrm{t\bar{t}H}$ production in hadron collisions

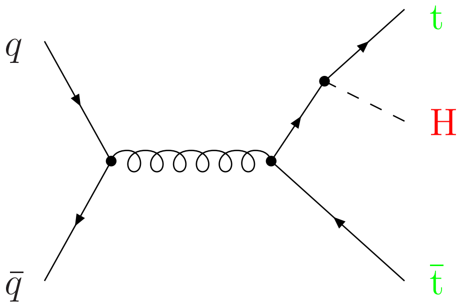
Typical LO diagrams:

... via gg fusion:





... via $q\bar{q}$ annihilation:



Present status of predictions:

- LO predictions — Kunszt '84, Dicus, Willenbrock '89; Gunion '91, Marciano, Paige '91

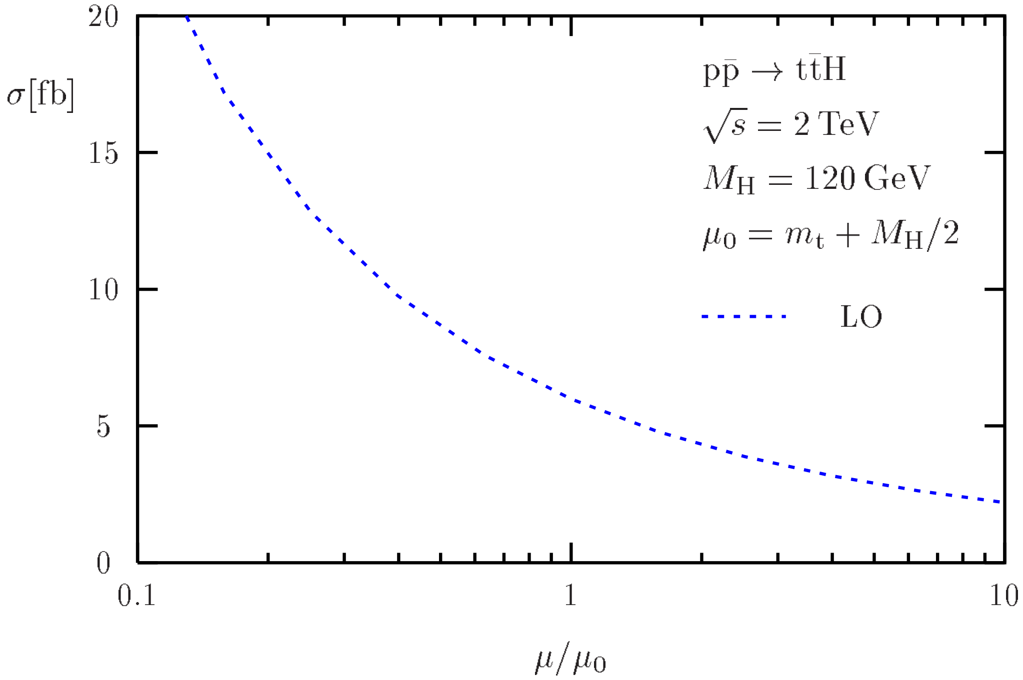
  $\hookrightarrow$ large scale dependence

  $\Rightarrow$ NLO prediction very important ! Calculated by two groups — Beenakker, S.D., Krämer, Plümper, Spira, Zerwas '01; Dawson, Reina, Wackeroth '01

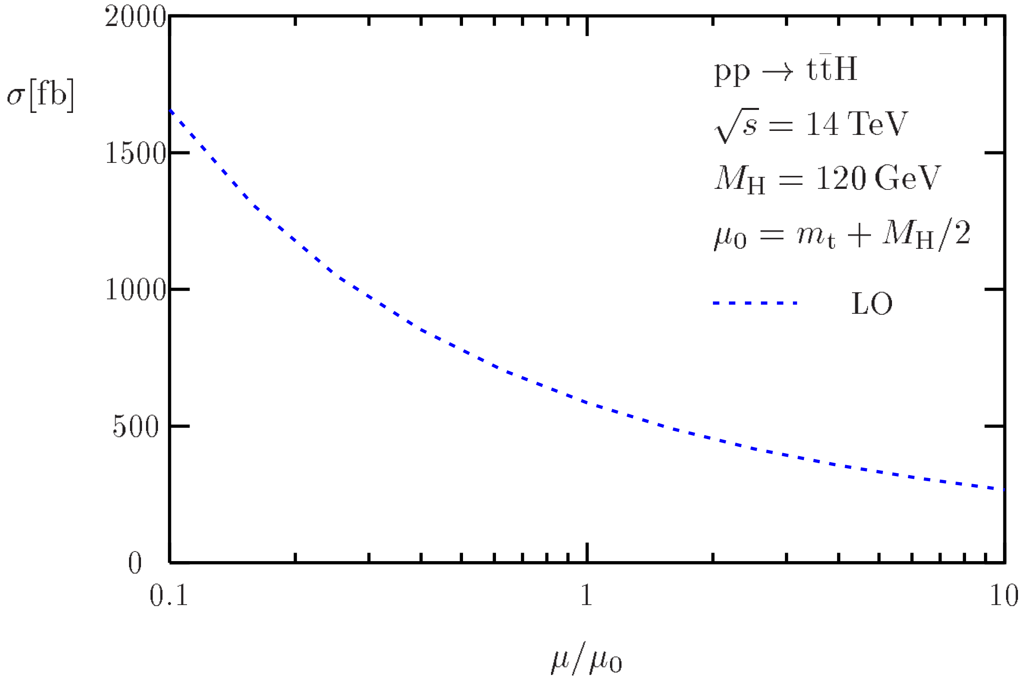
- Estimate of NLO corrections for $M_{\mathrm{H}} \ll m_{\mathrm{t}}$ in "equivalent Higgs approximation" — Dawson, Reina '98

Scale dependence of LO cross section

... at Tevatron: $\mu = \mu_{\rm ren} = \mu_{\rm fact}$



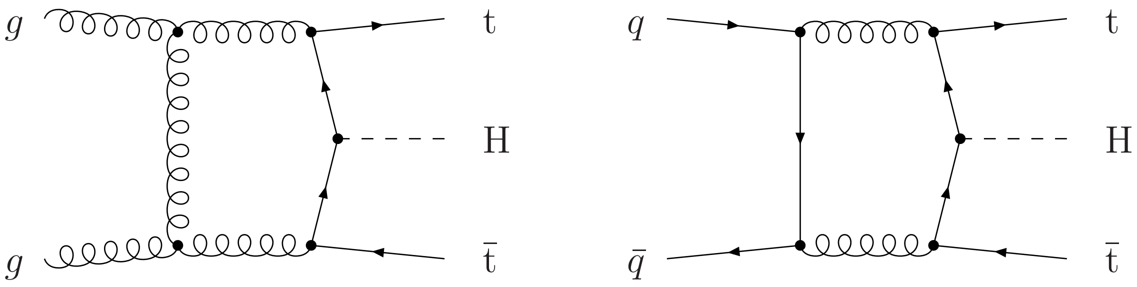
... at the LHC:



Large scale dependence !

Complications in the virtual corrections

Pentagon diagrams:



etc.

$\longrightarrow$ One-loop integrals of the form

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

Problems:

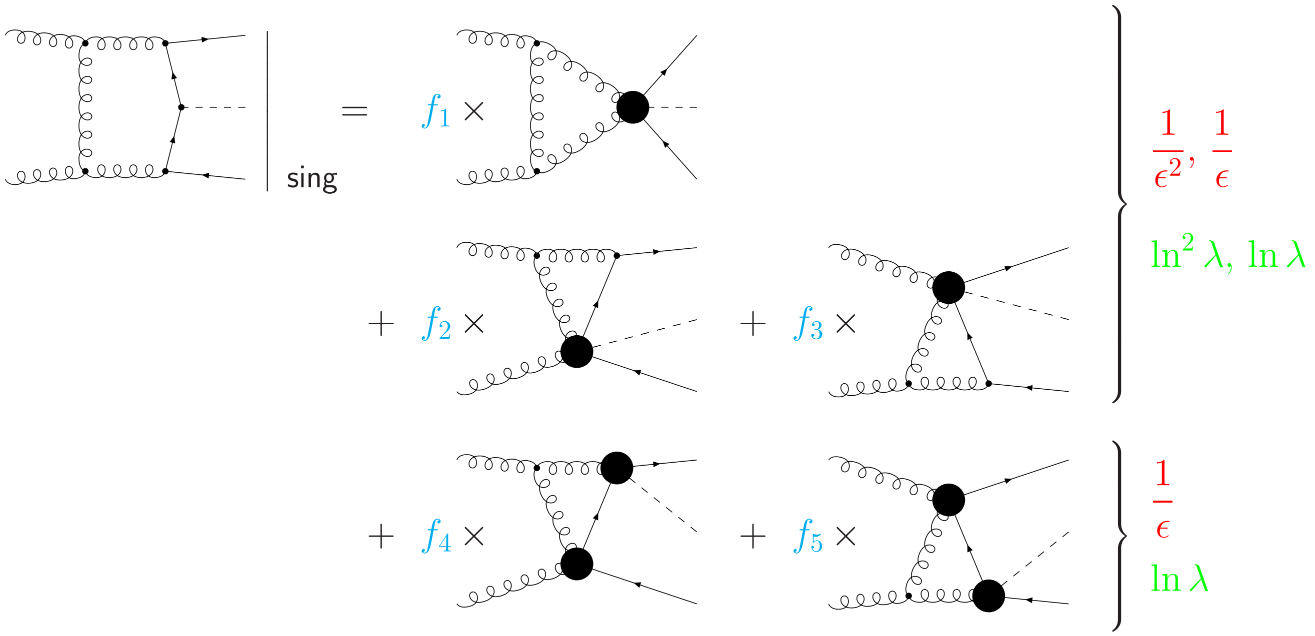
- scalar integral E_0:
  complicated singularity stucture (IR and collinear)
  needed: evaluation in D dimensions
  known: decomposition of E_0 into 4pt functions for $D = 4$ Melrose '65
  $\hookrightarrow$ trick: translate E_0 into mass regularization and
  continue in $D = 4$
- tensor integrals $E_{\mu\nu\ldots}$:
  Passarino–Veltman reduction to scalars possible but involved
  - subtlety: metric $g_{\mu\nu}$ spanned by external momenta for $D = 4$
    but not for $D \neq 4$
  - numerical instabilities
    due to lin. dependence of momenta on phase-space boundary
    solution:
    numerical extrapolation from safe to problematic regions

Strategy for calculating $E_0^{(D)}$ for $D = 4 - 2\epsilon$:

1. Generalize $E_0^{(D)}$ by introducing additional mass regulators λ
   e.g.: give internal g and q infinitesimal mass λ

2. Determine singular subdiagrams of $E_0^{(D,\lambda)}$
   by inspecting soft and collinear limits in momentum space

   Example: singularities of $E_0^{(D)}$ / $E_0^{(D=4,\lambda)}$



f_i = simple kinematical factors

3. Calculate $E_0^{(D)}$
   from regularization-scheme-independent expression:

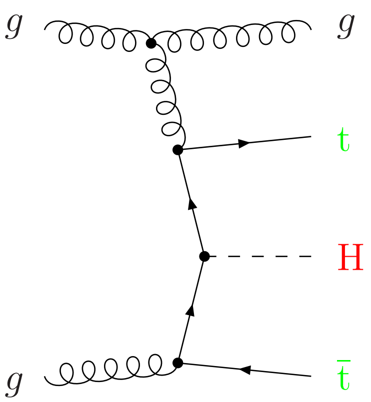
$$\left[E_0^{(D,\lambda)} - E_{0,\text{sing}}^{(D,\lambda)} \right] \Bigg|_{\substack{D \to 4 \\ \lambda \to 0}} = \text{finite}$$

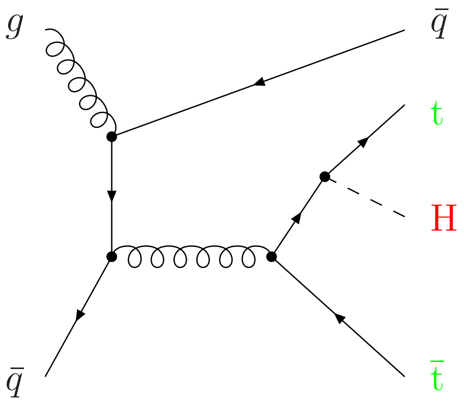
$$\Rightarrow \quad E_0^{(D)} = E_{0,\text{sing}}^{(D)} + \left[E_0^{(D=4,\lambda)} - E_{0,\text{sing}}^{(D=4,\lambda)} \right] \Bigg|_{\lambda \to 0} + \mathcal{O}(\epsilon)$$

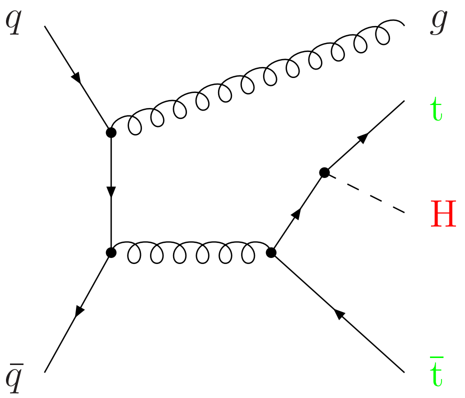
$$= \text{combination of 3pt and 4pt functions}$$

Real corrections

Typical diagrams:







etc.

Problems:

- evaluation of complex matrix elements
  $\hookrightarrow$ application of conventional trace techniques and use of package *Madgraph* Stelzer, Long '94
- extraction of soft and collinear divergences and factorization

  $\hookrightarrow$ use generalization of dipole subtraction formalism

  additional check: use of phase-space slicing for $q\bar{q}$ channel

Dipole subtraction formalism

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

worked out for

- QCD with massless partons
  Catani, Seymour '96
- γ radiation off massive fermions
  S.D. '99

} QCD with massive partons
Phaf, Weinzierl '01
Catani, S.D., Seymour, Trócsányi '02

basic idea: NLO correction to process with m partons

$$\sigma^{\rm NLO} = \underbrace{\int_{m+1}\left[{\rm d}\sigma^{\rm real} - {\rm d}\sigma^{\rm sub}\right]}_{\text{finite}} + \underbrace{\int_{m}\left[{\rm d}\sigma^{\rm virtual} + {\rm d}\bar\sigma_1^{\rm sub}\right]}_{\text{finite}}$$

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

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

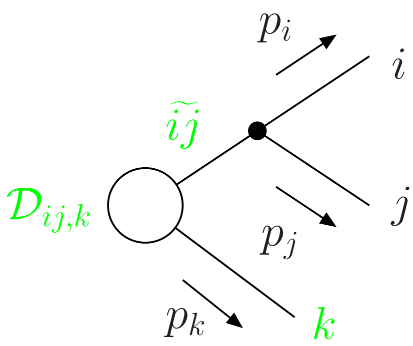
- sum rule:

$$-\int_{m+1}{\rm d}\sigma^{\rm sub} + \int_m {\rm d}\bar\sigma_1^{\rm sub} + \int_0^1 {\rm d}x \int_m \left({\rm d}\bar\sigma^{\rm sub}(x)\right)_+ = 0$$

- asymptotics:

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

Construction of $\mathrm{d}\sigma^{\mathrm{sub}}$:



"dipole" $(\widetilde{ij}, k)$

$$\int \mathrm{d}\sigma^{\mathrm{sub}} = \sum_{\text{dipoles}} \int \mathrm{d}\sigma^{\mathrm{LO}} \underset{\uparrow}{\otimes} \mathcal{D}_{ij,k}(p_i, p_j, p_k)$$

Color and spin correlations in $\mathrm{d}\sigma^{\mathrm{LO}}$

IR-singular limits:

- soft limit: $p_i \to 0$

$$\mathcal{D}_{ij,k} + \mathcal{D}_{ik,j} \quad \sim \quad \text{const.} \times \frac{p_j \cdot p_k}{(p_i \cdot p_j)(p_i \cdot p_k)}$$

"eikonal factor"

- collinear limit: $p_i \cdot p_j \to 0, \; m_{i,j,ij} \to 0$

$$\mathcal{D}_{ij,k} \quad \sim \quad \frac{\text{const.}}{(p_i + p_j)^2 - m_{ij}^2} \times \hat{P}_{\widetilde{ij},i}(p_i, p_j)$$

Altarelli–Parisi function

main difficulties:

- phase-space embedding: $\int \mathrm{d}\Phi_{m+1} = \int_0^1 \mathrm{d}x \int \mathrm{d}\Phi_m(x) \int [\mathrm{d}p_i(x)]$
- analytical integration of $\int_0^1 \mathrm{d}x \int [\mathrm{d}p_i(x)]$:

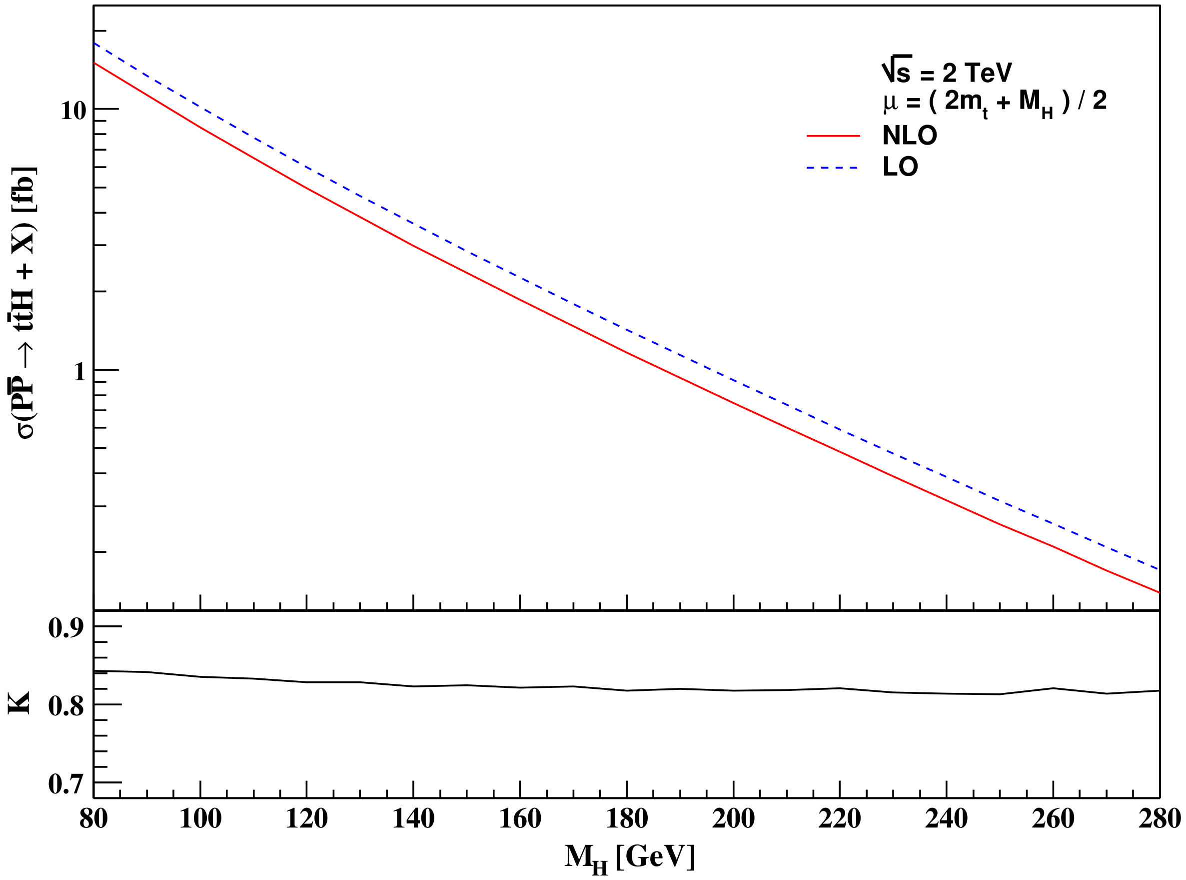
$$\int \mathrm{d}\bar{\sigma}^{\mathrm{sub}}(x) = \int \mathrm{d}\sigma^{\mathrm{LO}} \otimes \int [\mathrm{d}p_i(x)] \, \mathcal{D}_{ij,k}(p_i, p_j, p_k)$$

$$\mathrm{d}\bar{\sigma}_1^{\mathrm{sub}} = \int_0^1 \mathrm{d}x \, \mathrm{d}\bar{\sigma}^{\mathrm{sub}}(x)$$

Numerical results for NLO predictions

NLO cross section at the Tevatron

Beenakker, S.D., Krämer, Plümper, Spira, Zerwas '01



Default choice for scale $\mu = \mu_{\text{ren}} = \mu_{\text{fact}}$:

$$\mu = \mu_0 = (2m_{\text{t}} + M_{\text{H}})/2 = \text{half of threshold energy}$$

Relative correction for $\mu = \mu_0$

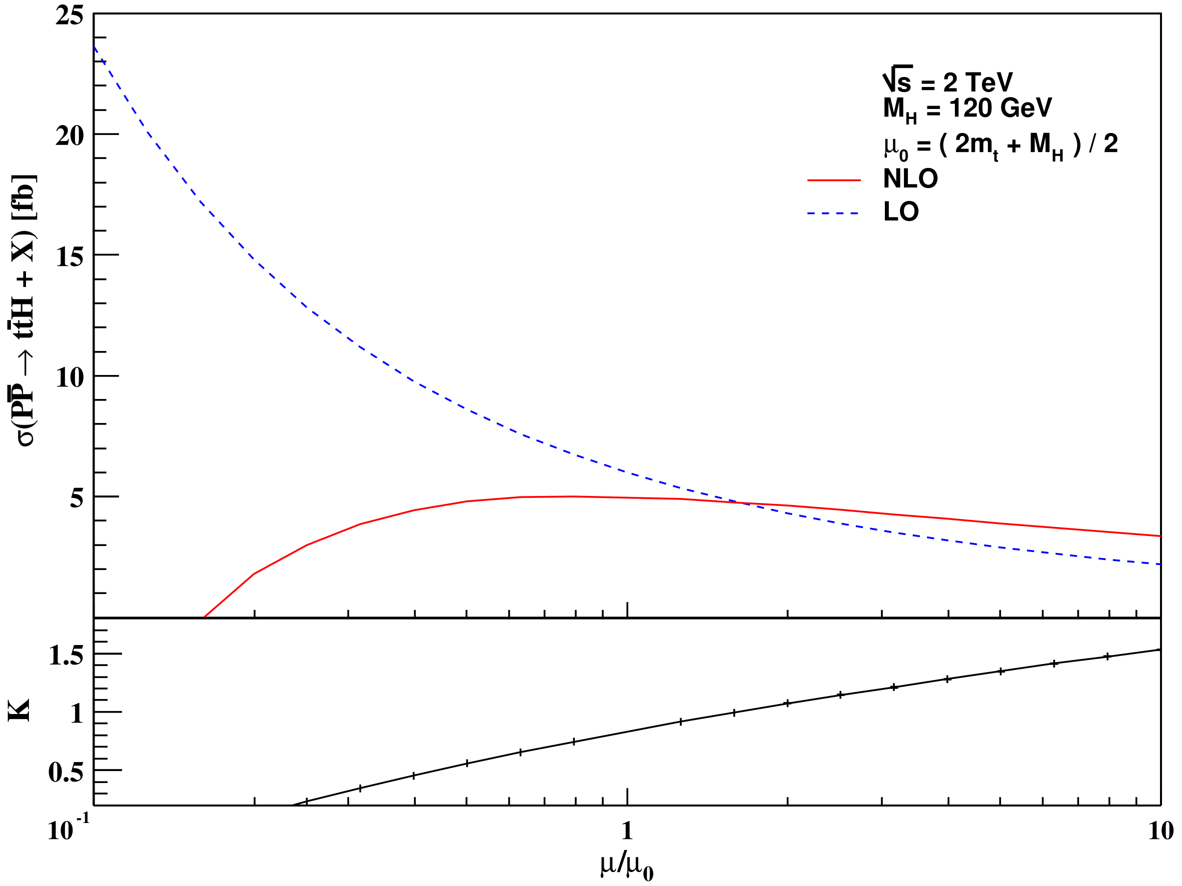
$$K \;=\; \frac{\sigma_{\text{NLO}}}{\sigma_{\text{LO}}} \;\sim\; 0.8$$

Remarks:

- $q\bar{q}$ channel strongly dominates LO and NLO cross section
- confirmed by result of Dawson, Reina, Wackeroth
  based on $q\bar{q}$ channel only

Scale dependence of NLO cross section at the Tevatron

Beenakker, S.D., Krämer,
Plümper, Spira, Zerwas '01



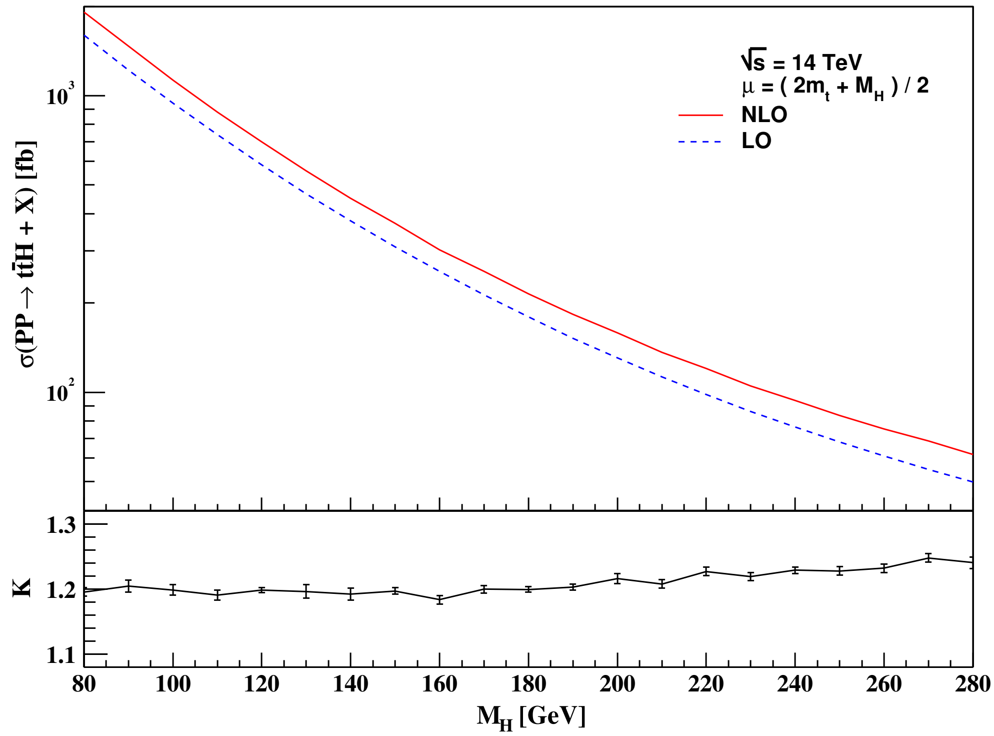
Scale variation within $\mu_0/3 \lesssim \mu \lesssim 3\mu_0$:

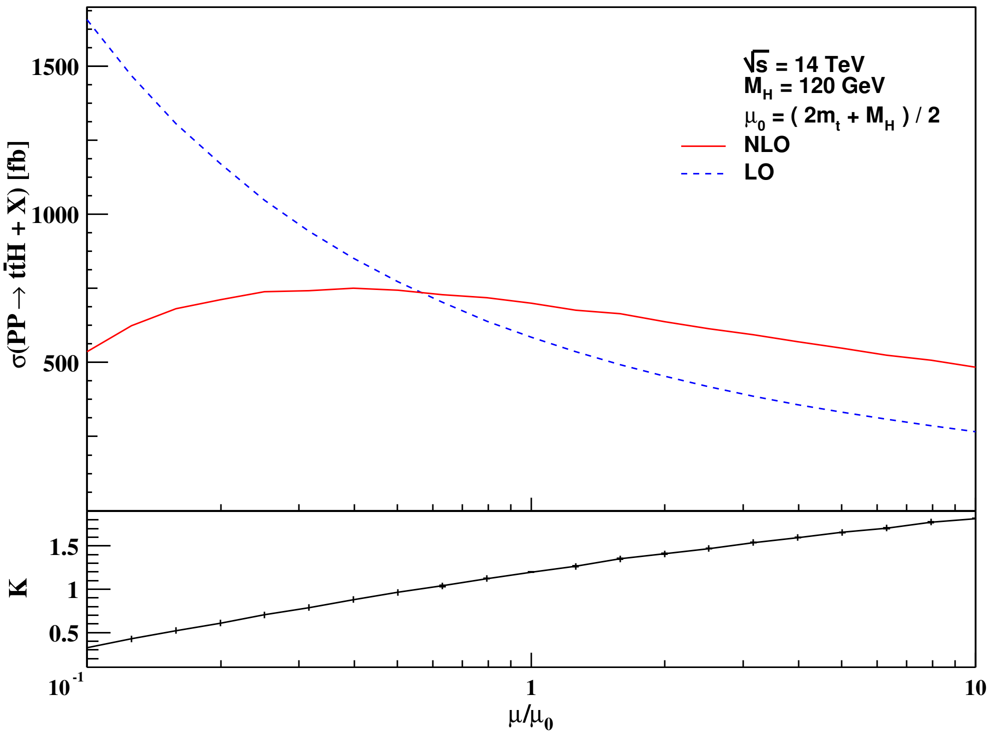
$$\frac{\Delta\sigma_{\rm LO}}{\sigma_{\rm LO}} \sim 2-3, \qquad\qquad \frac{\Delta\sigma_{\rm NLO}}{\sigma_{\rm NLO}} \sim 20\%$$

Drastic reduction of scale dependence

NLO cross section at the LHC

Beenakker, S.D., Krämer, Plümper, Spira, Zerwas '01

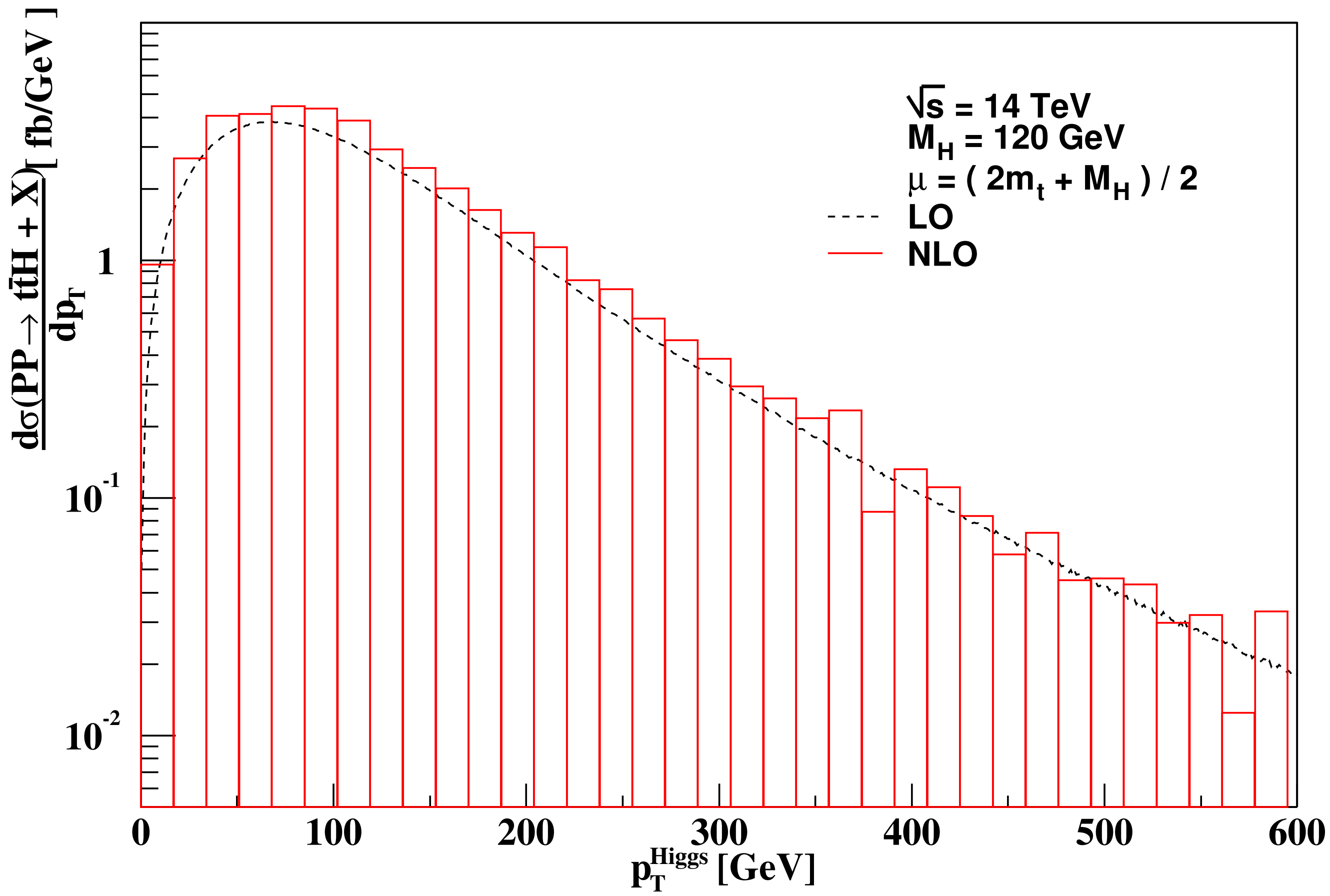




Stabilization of prediction in NLO similar to Tevatron case

Higgs transverse-momentum distribution in NLO at the LHC

Beenakker, S.D., Krämer, Plümper, Spira, Zerwas '02

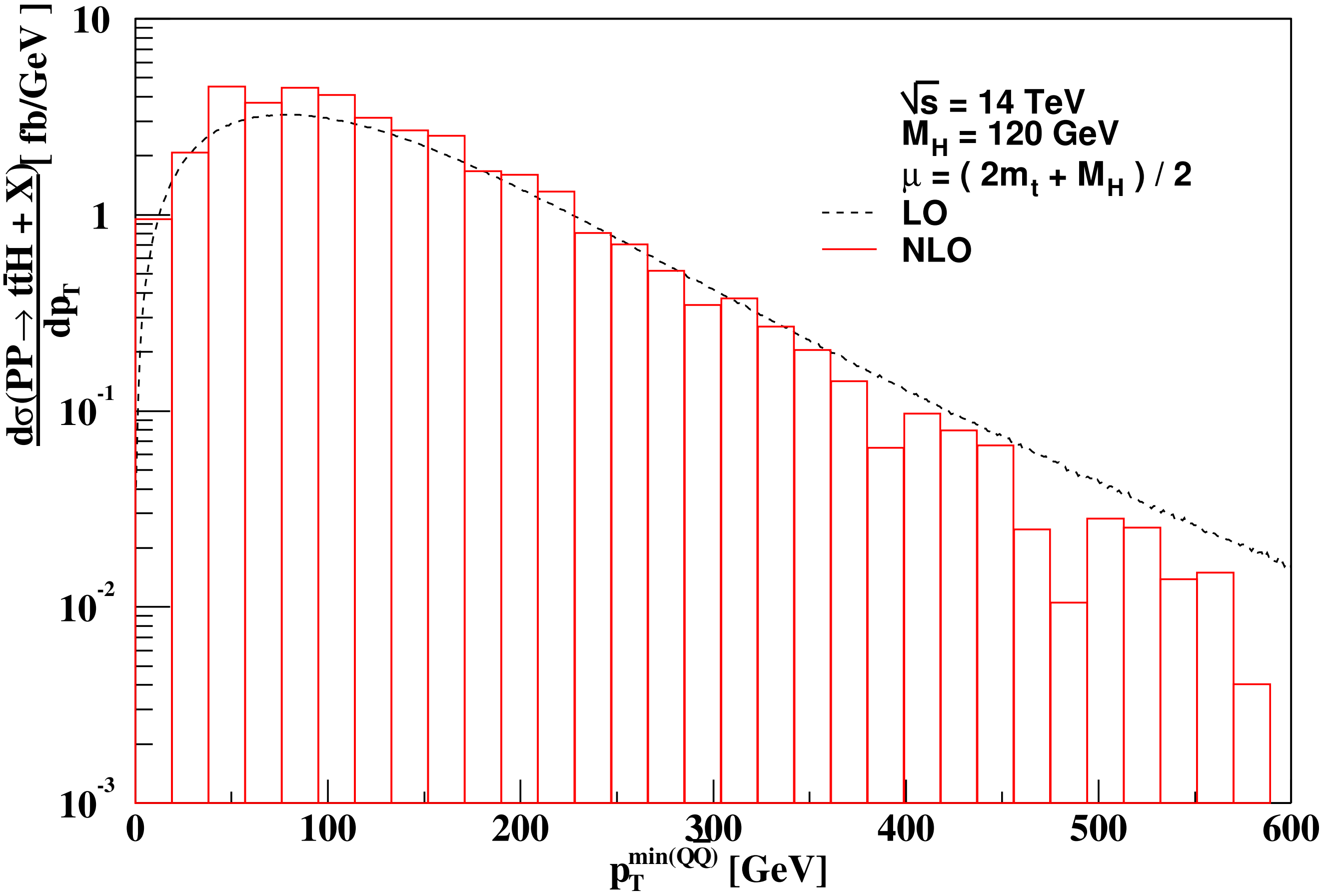


Note:

K-factor rescaling of LO prediction is good approximation for NLO.

Example for top-quark transverse-momentum distribution

Beenakker, S.D., Krämer, Plümper, Spira, Zerwas '02

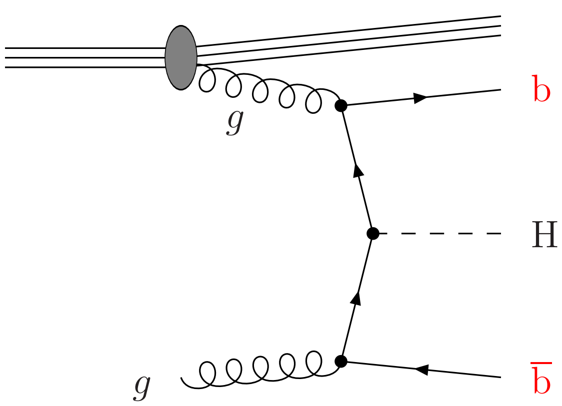


Note:

NLO correction does not result from LO by simple K-factor rescaling.

3 Outlook to $\mathrm{b\bar{b}H}$ production in hadron collisions

Problem under discussion:



small $p_{\mathrm{b,T}}$ leads to large
terms $\propto \alpha_{\mathrm{s}} \ln(m_{\mathrm{b}}^2/M_{\mathrm{H}}^2)$

2 complementary approaches:

1. Fully inclusive approach:

   Resummation of $\alpha_{\mathrm{s}} \ln(m_{\mathrm{b}}^2/M_{\mathrm{H}}^2)$ terms by
   introduction of b-quark density $\mathrm{b}(x, \mu_{\mathrm{fact}})$ with GLAP evolution
   (i.e. $g \longrightarrow \mathrm{b\bar{b}}$ splitting process viewed as part of proton)

   - LO process: $\mathrm{b\bar{b}} \longrightarrow \mathrm{H}$
   - 2 types of corrections:
     - pure $\mathcal{O}(\alpha_{\mathrm{s}}^n)$ corrections
     - corrections to $g \longrightarrow \mathrm{b\bar{b}}$ splitting ($g\mathrm{\bar{b}} \longrightarrow \mathrm{bH}$, etc.)
   - Strategy is well defined
     and double-counting can be avoided.

     Dicus, Stelzer, Sullivan, Willenbrock '98
   - Shortcomings:
     - intrinsic p_{T} of b quarks neglected in b density
     - approach not adequate if small $p_{\mathrm{b,T}}$ not dominating

2. Approach for tagged b quarks:

Requirement: $p_{\mathrm{b,T}} > p_{\mathrm{T,min}} > \mathcal{O}(m_{\mathrm{b}})$

- Approach more realistic than fully inclusive treatment
- Problematic terms more moderate: $\propto \alpha_{\mathrm{s}} \ln(p_{\mathrm{T,min}}^2/M_{\mathrm{H}}^2)$

  $\Rightarrow$ purely perturbative approach reasonable
  (make use of NLO results for $\mathrm{t\bar{t}H}$ case)
- Resummation of terms $\alpha_{\mathrm{s}} \ln(p_{\mathrm{T}}^2/M_{\mathrm{H}}^2)$ desirable
- Danger: too much signal lost by p_{T} cut?

Remark:

Intermediate case possible: only one b quark tagged

$\hookrightarrow$ relevant process $bg \to bH$,
cross section larger than for $gg, q\bar{q} \to \mathrm{b\bar{b}H}$

Campbell, R.K.Ellis,
Maltoni, Willenbrock '02

But: problem with b parton density also involved

First steps of solution:

- study p_{T} distributions of b quarks in $\mathrm{b\bar{b}H}$ production
- study phenomenological relevance of approach with all b's tagged

... work in progress

4 Summary

$\mathrm{t\bar{t}H}$ production:

- important channel for Higgs searches at Tevatron and the LHC
- LO predictions have large scale uncertainties ($> 100\%$)
- NLO presented recently

  $\hookrightarrow$ significant reduction of scale uncertainties ($\sim 20\%$)

$\mathrm{b\bar{b}H}$ production:

- particular importance in SUSY models for large $\tan\beta$
- total cross section partially contained in $\mathrm{b\bar{b}} \to \mathrm{H}$

  but: $q\bar{q}, gg \to \mathrm{b\bar{b}H}$ relevant for b's with finite p_{T}

  problem: b-quark density versus b quarks with finite p_{T}
- NLO predictions in progress