Inclusive Higgs Production at Hadron Colliders

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Motivation

The Standard Model is ~35 years old and its essential goal

To describe electroweak interactions with a spontaneously broken $SU(2)\otimes U(1)$ gauge symmetry

has been spectacularly confirmed

- Renormalizability
- Discovery of Neutral Currents
- Discovery of W and Z bosons
- Precision test of W/Z properties

The Standard Model Higgs boson is the benchmark for studies of the symmetry breaking sector

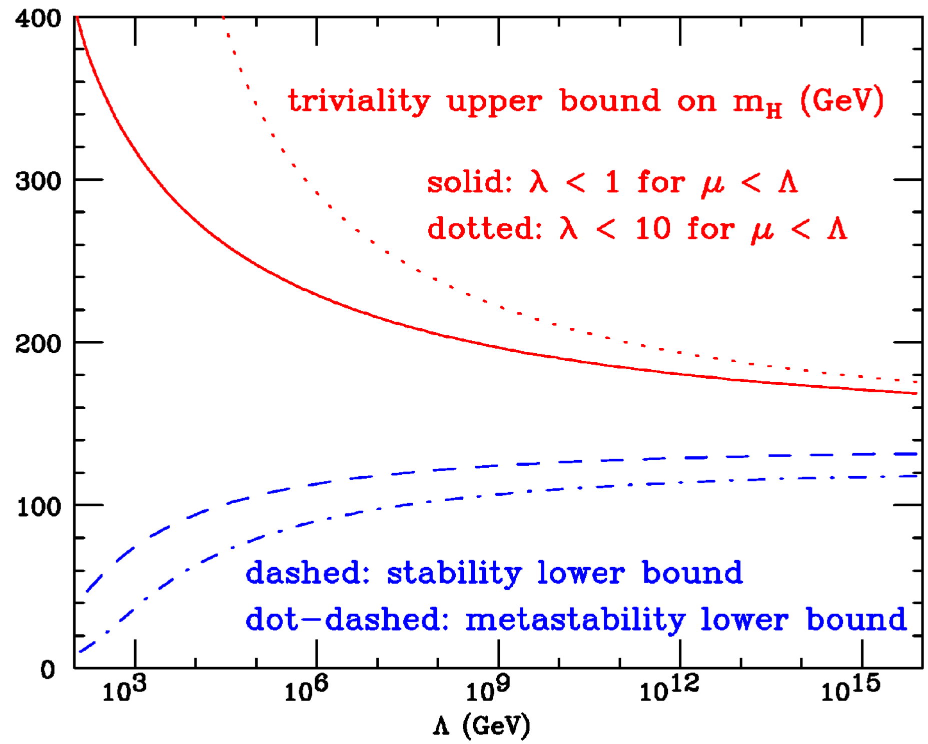
Where should the Higgs be?

LEP Search: $M_H \geq$ 114.1 GeV ((M_H = 115 GeV?)

Precision EW Fits: $M_H = 85^{+54}_{-34}$ GeV

95% CL upper limit: $M_H <$ 196 GeV

Theoretical Bounds:
- Triviality
- Vacuum Stability

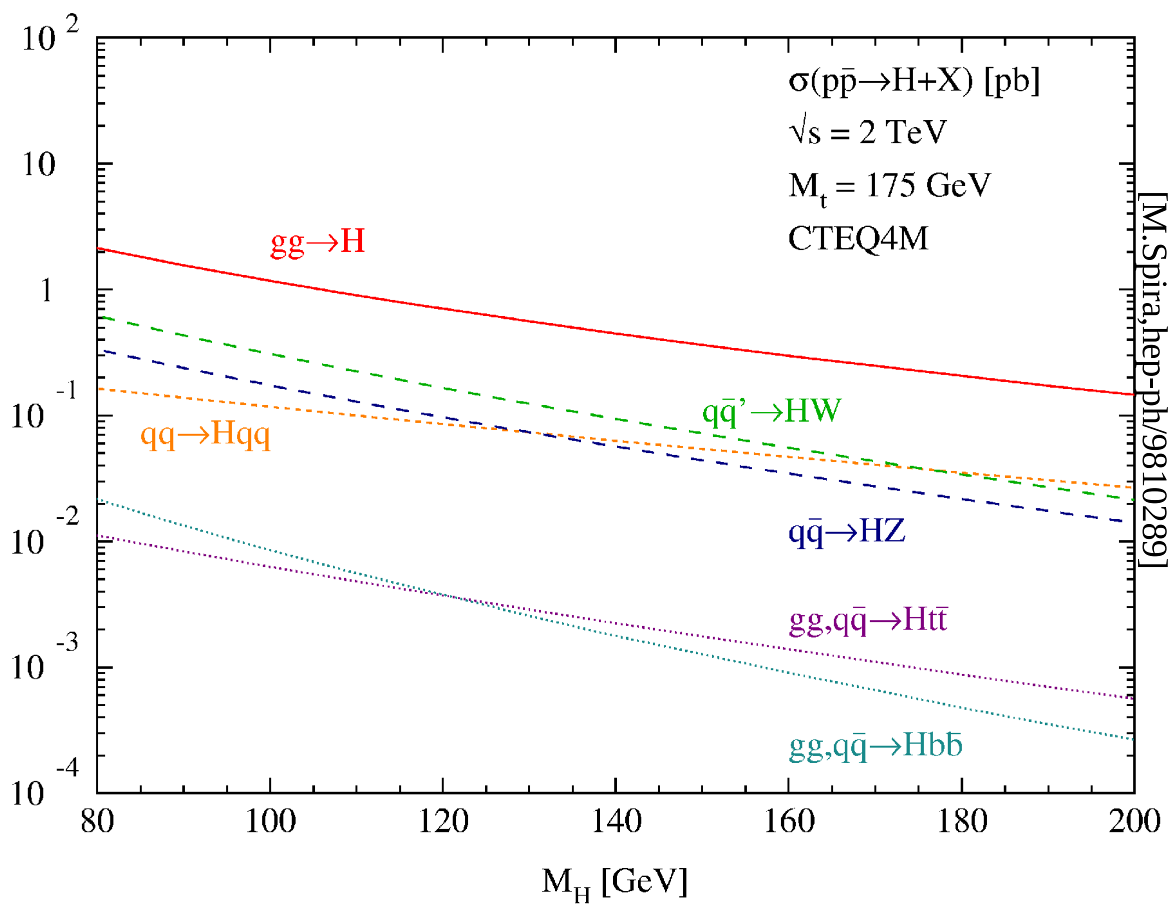


[G. Ridolfi, hep-ph/0106300]

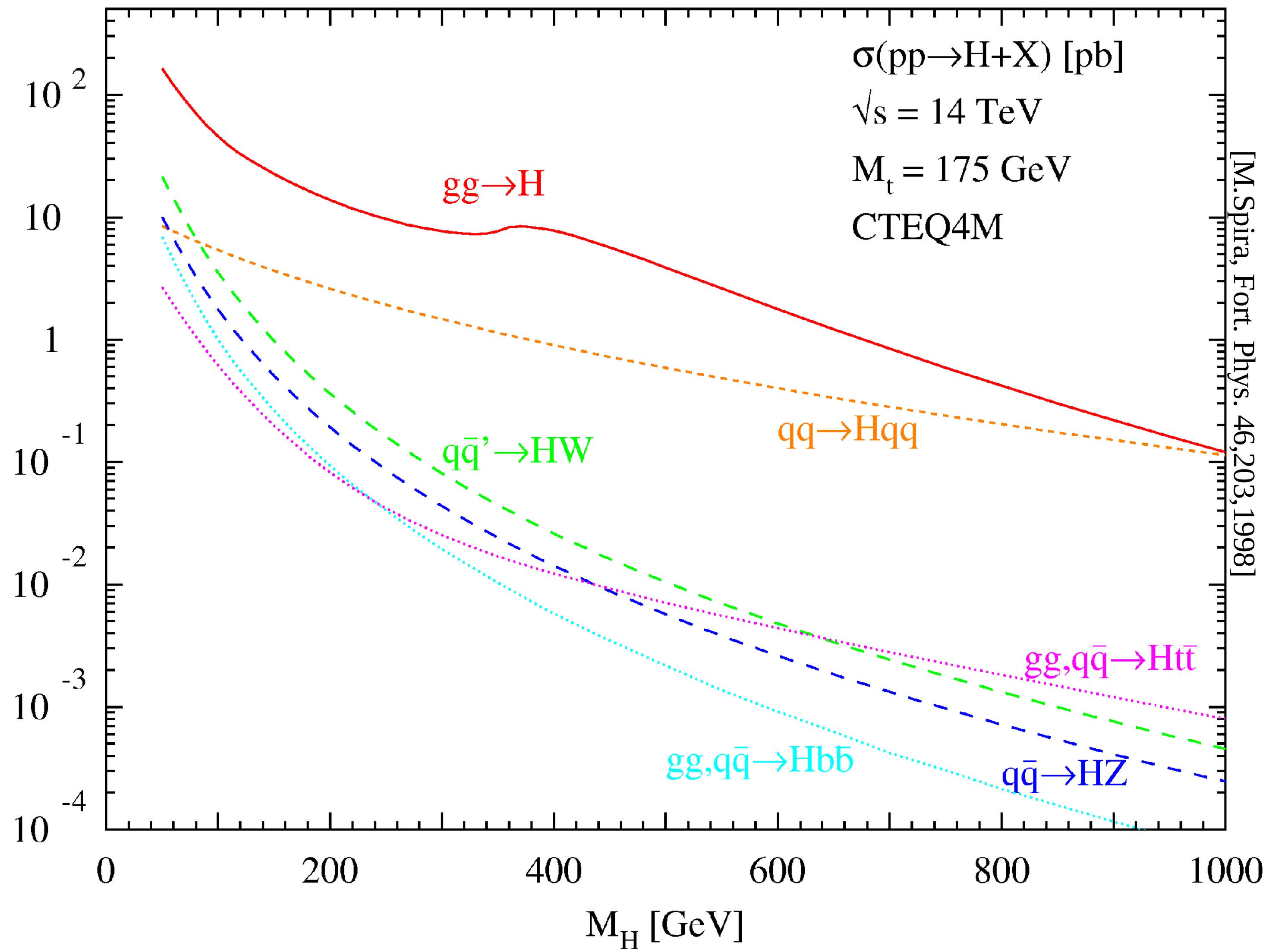
Higgs Production at Hadron Colliders

Gluon Fusion dominates Higgs production at Hadron Colliders

At the Tevatron:

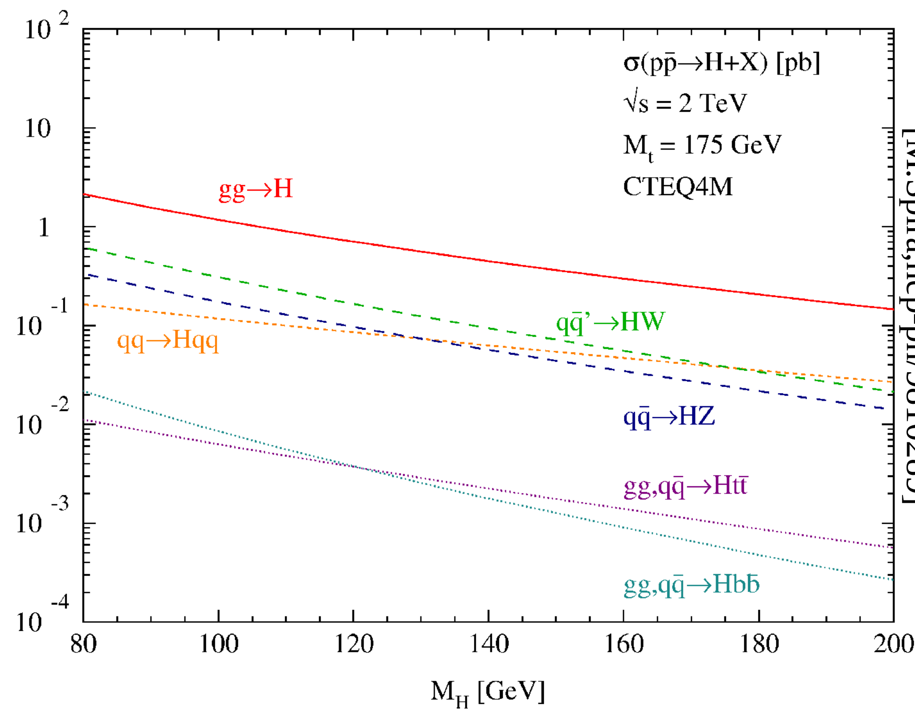


And at the LHC



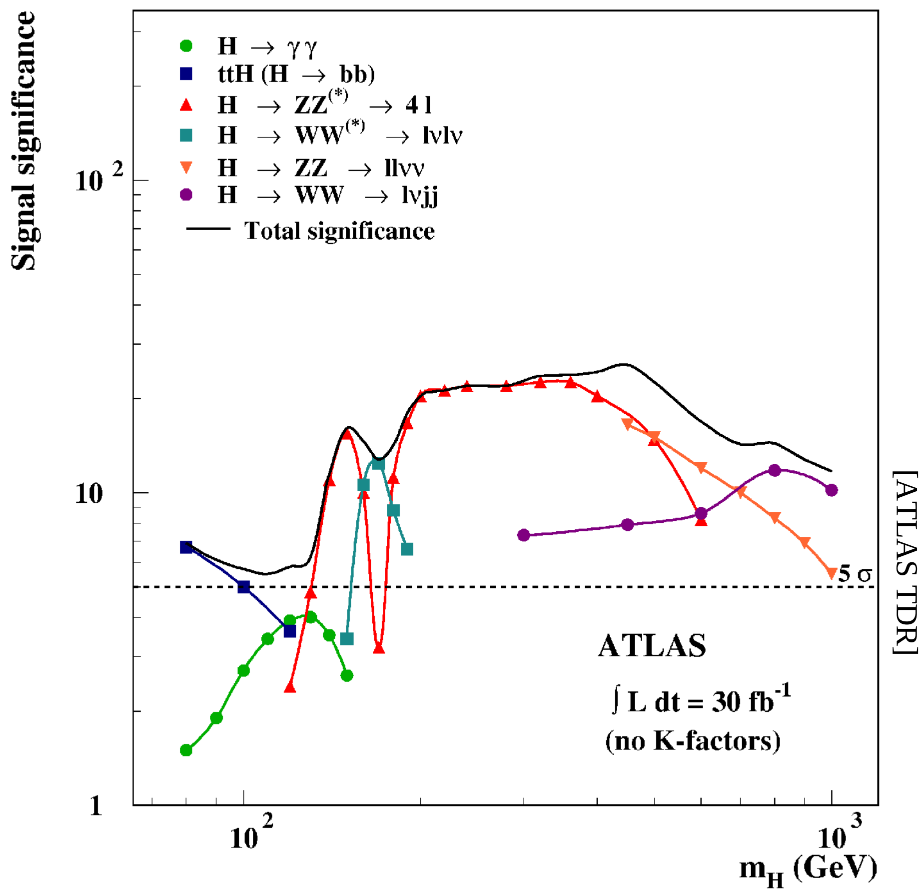
At the Tevatron, $H\to b\bar{b}$ decay is overwhelmed by QCD background and the rate is too low to observe rare decays like $H \to \gamma\gamma$.

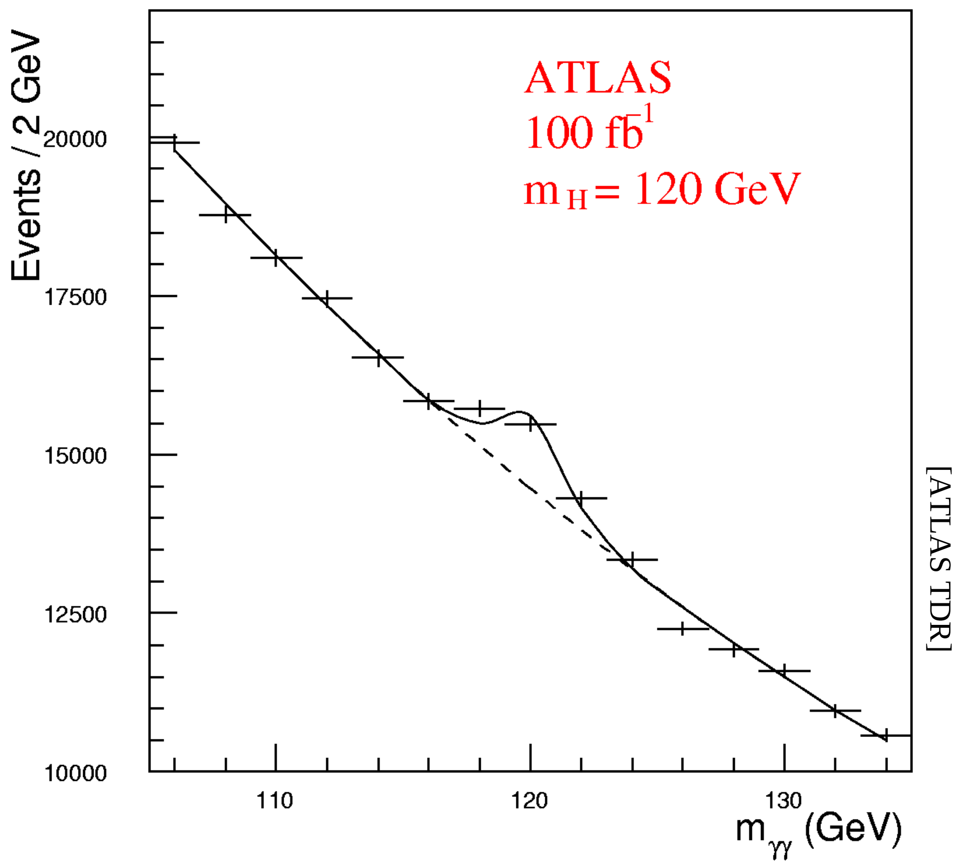
Except near the $H\to WW$ threshold
($140\ \text{GeV} \leq M_H \leq 170\ \text{GeV}$)
associated production
($q\bar{q}\to HW$) is better.



[M.Spira,hep-ph/9810289]

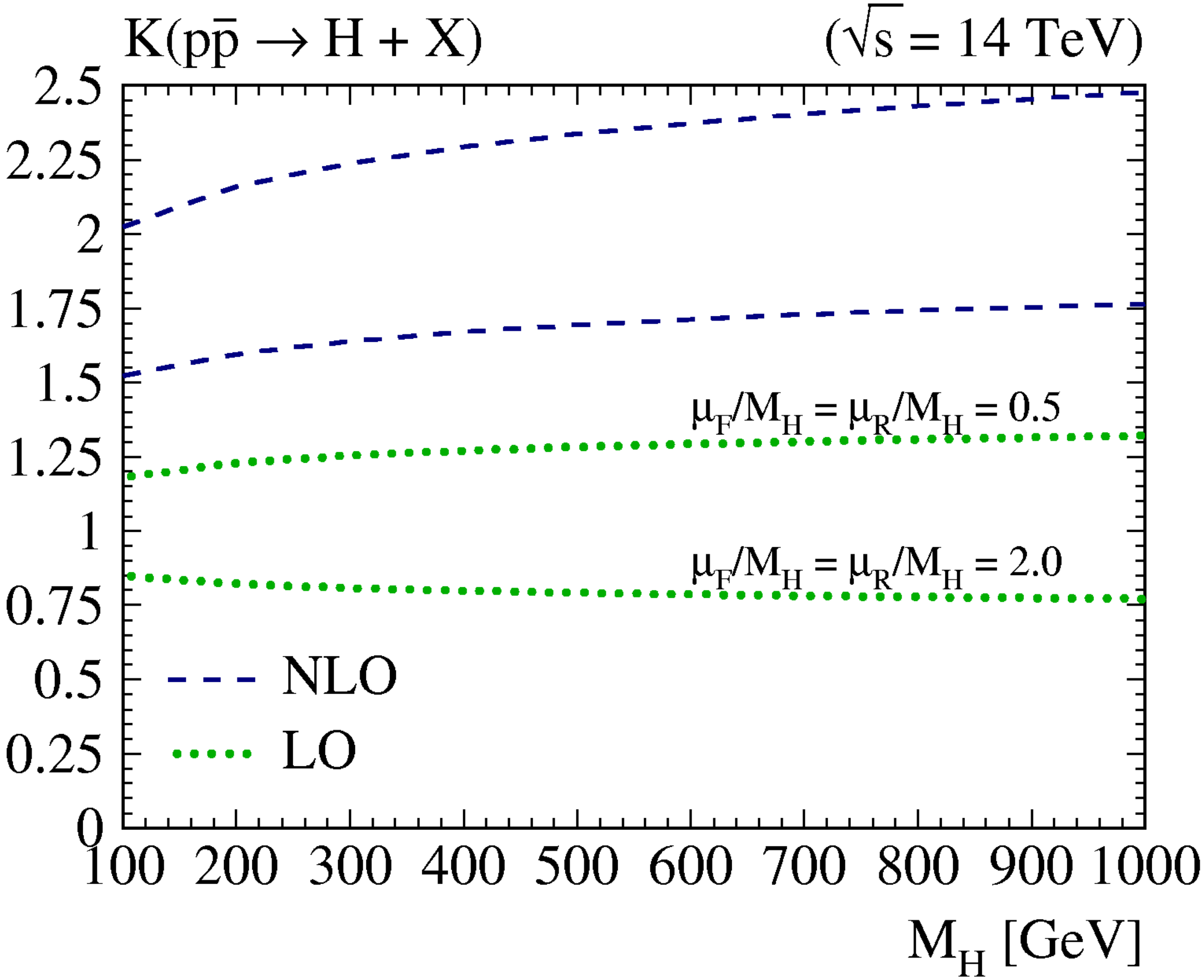
At LHC gg→H is the primary discovery mode



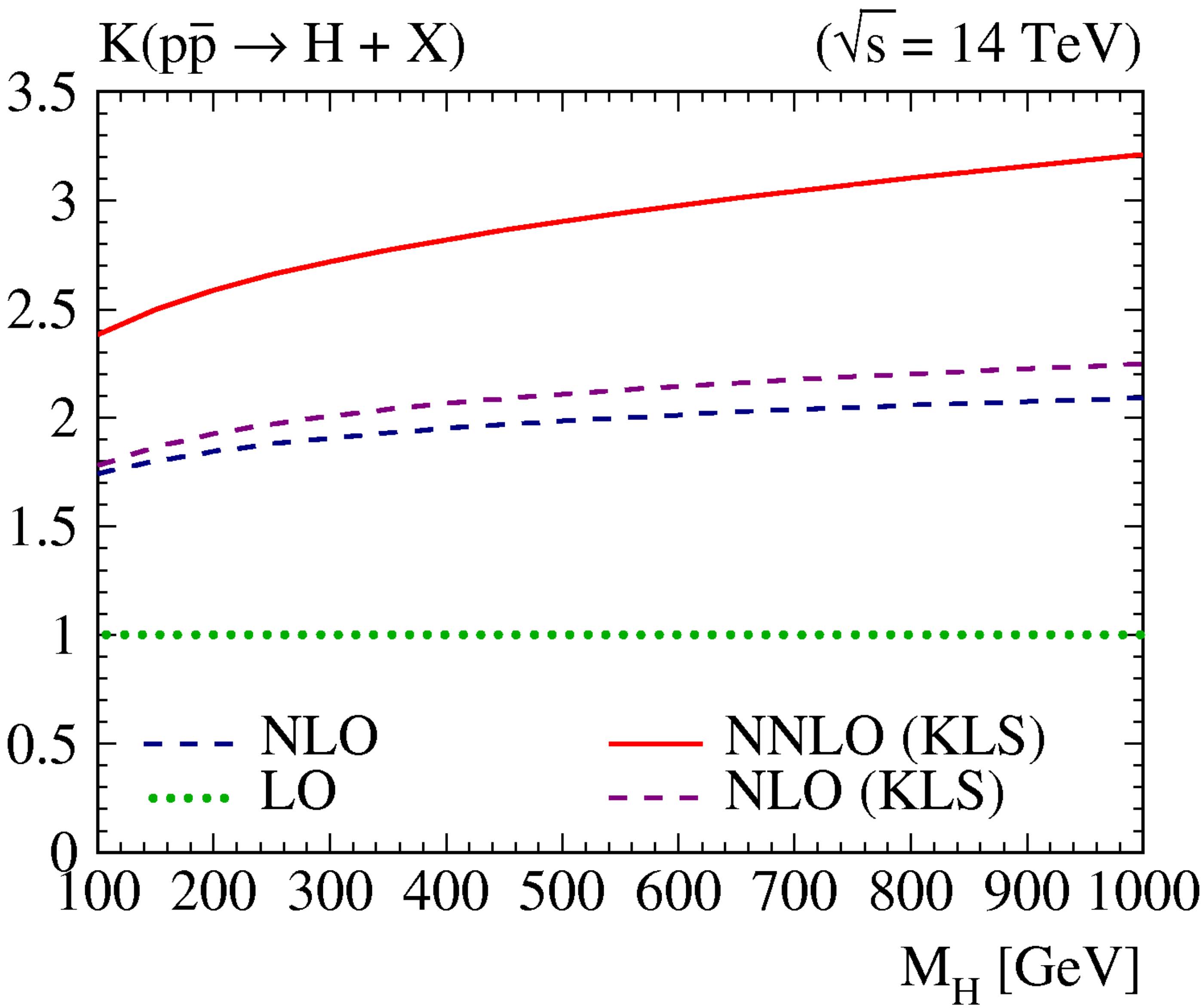


Why NNLO?

The NLO Corrections are very large



And NNLO was estimated (KLS) to be much larger

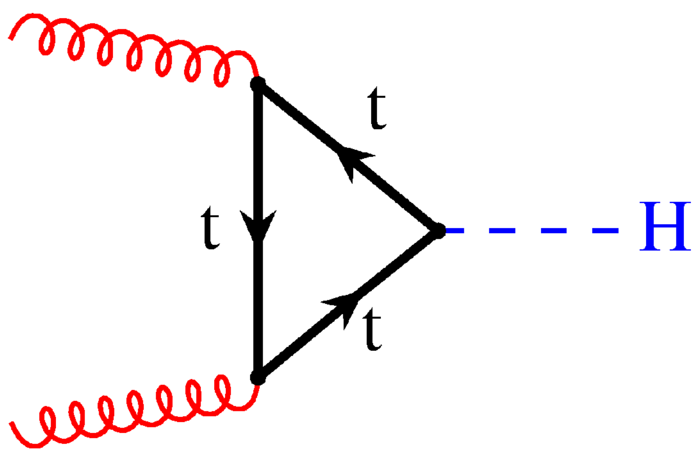


Methods

The Higgs boson couples to mass:

- The gluons have no direct coupling
- The quarks in the proton (u,d,s) have tiny couplings

Hadronic Higgs production is dominated by gluons interacting through virtual top quark loops.



Effective Lagrangian

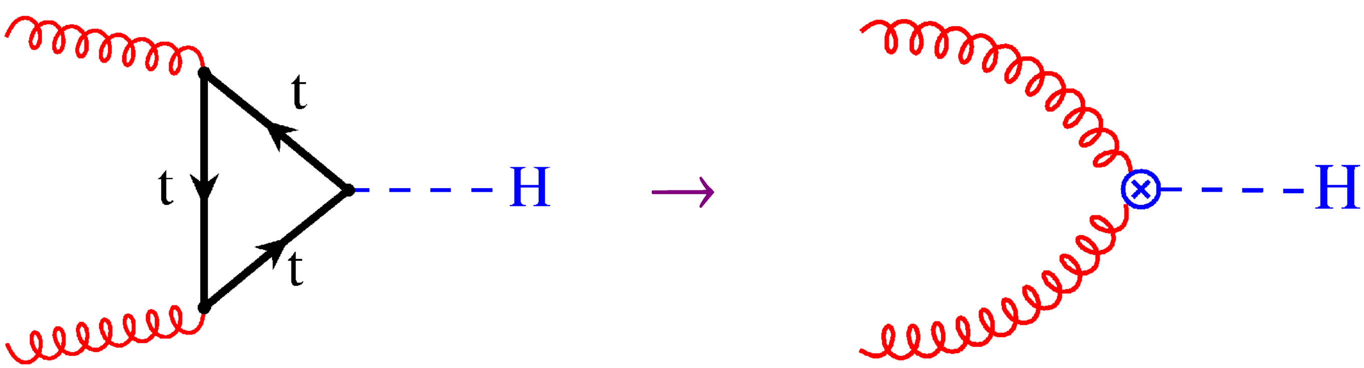
In the limit that the top quark is very heavy and all other quarks are massless, we can integrate out the top and formulate an effective Lagrangian coupling the Higgs to Gluons.

$$\mathcal{L} = C_1 \, H \, G^{\mu\nu} \, \mathbf{G}_{\mu\nu}$$

[Vainshtein et al.]

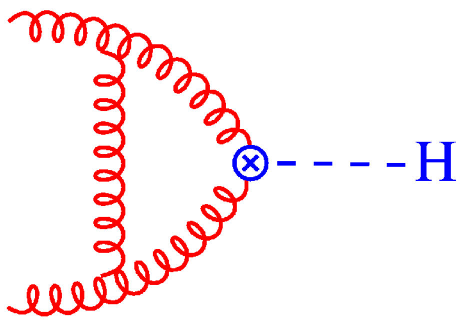
C_1 has been computed to order α_s^4 ! [Chetyrkin et al.]

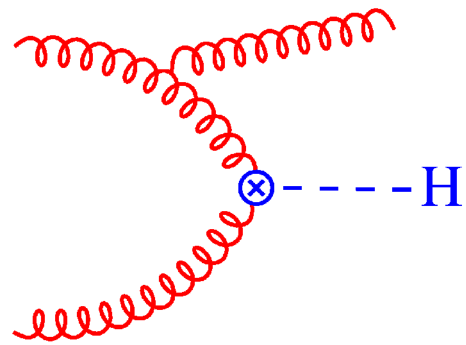
Using the effective Lagrangian greatly simplifies the calculation of radiative corrections.



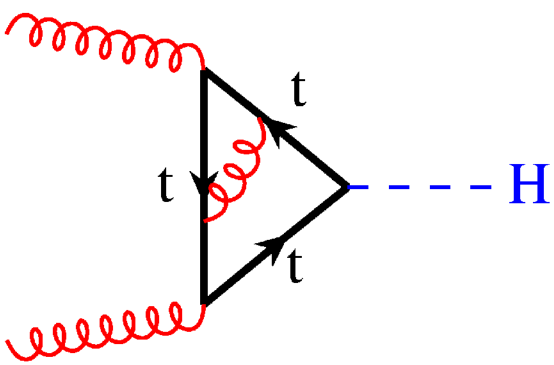
NLO Corrections

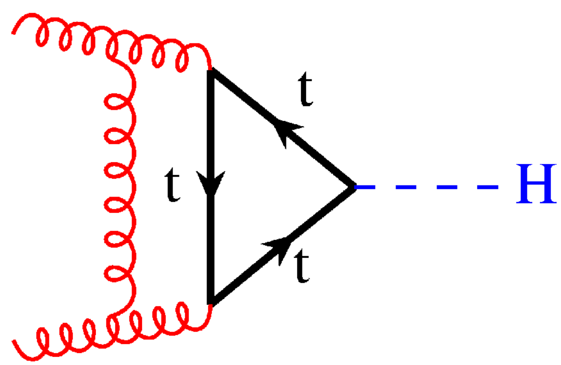
NLO Corrections have been computed in both the effective Lagrangian (Dawson; Djouadi et al.)



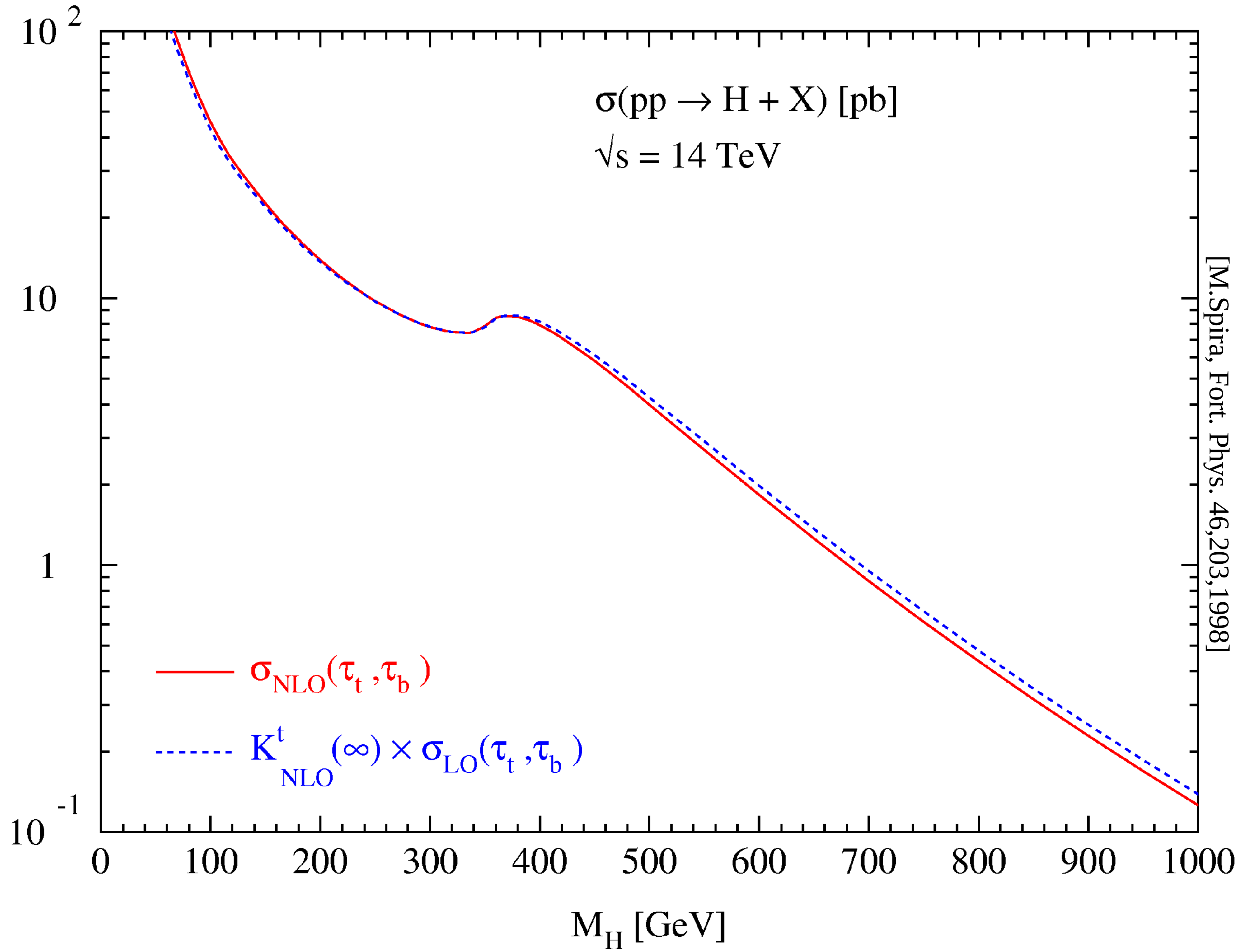


and in the full theory (Djouadi et al.)





They agree extremely well



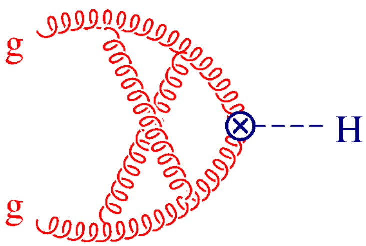
NNLO Corrections

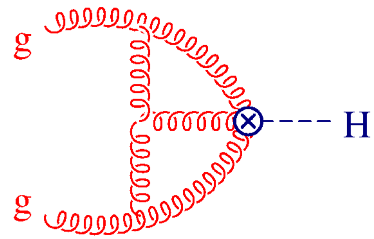
For NNLO corrections, we assume that the Effective Lagrangian provides a good description of Higgs Production (especially in the most interesting mass range (< 200 GeV)).

NNLO Corrections combine three components

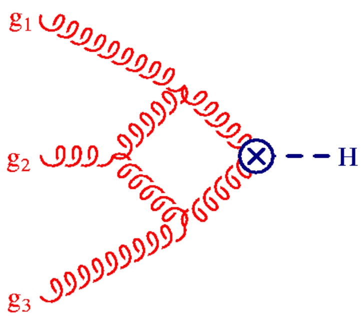
- Virtual corrections to two loops
- Single Real Emission corrections to one loop
- Double Real Emission corrections

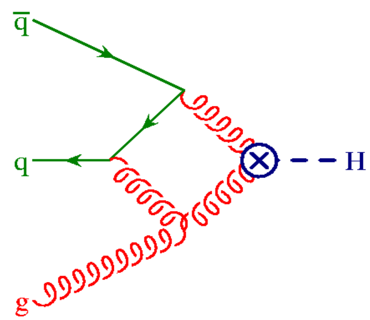
Virtual Corrections:



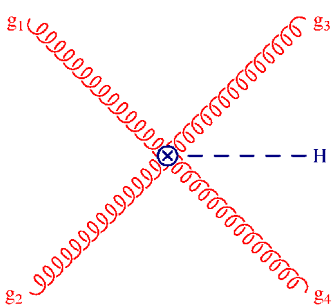


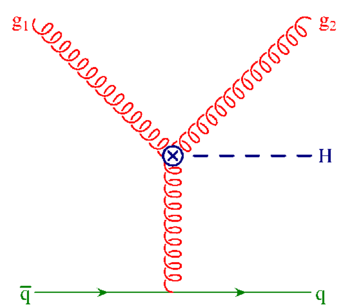
One-loop Single Real Emission:

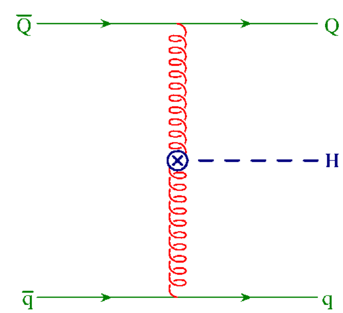




Double Real Emission:







Power Series Expansion in (1-x)

The cross section can be written as a power series in (1-x), ln(1-x):

$$x \equiv \frac{M_H^2}{\hat{s}}$$

$$\hat{\sigma}_{ij} = \sum_{n\geq 0} \left(\frac{\alpha_s}{\pi}\right)^n \hat{\sigma}_{ij}^{(n)} ,$$

$$\hat{\sigma}_{ij}^{(n)} = \left[a^{(n)}\,\delta(1-x) + \sum_{k=0}^{2n-1} b_k^{(n)} \left[\frac{\ln^k(1-x)}{1-x}\right]_+ + \sum_{l=0}^{\infty}\sum_{k=0}^{2n-1} c_{lk}^{(n)}\,(1-x)^l \ln^k(1-x) \right]$$

In the Soft limit, one keeps only the $a^{(n)}$ and $b_k^{(n)}$ terms.

In the Soft + Collinear limit (SVC), one also keeps $c_{03}^{(2)}$

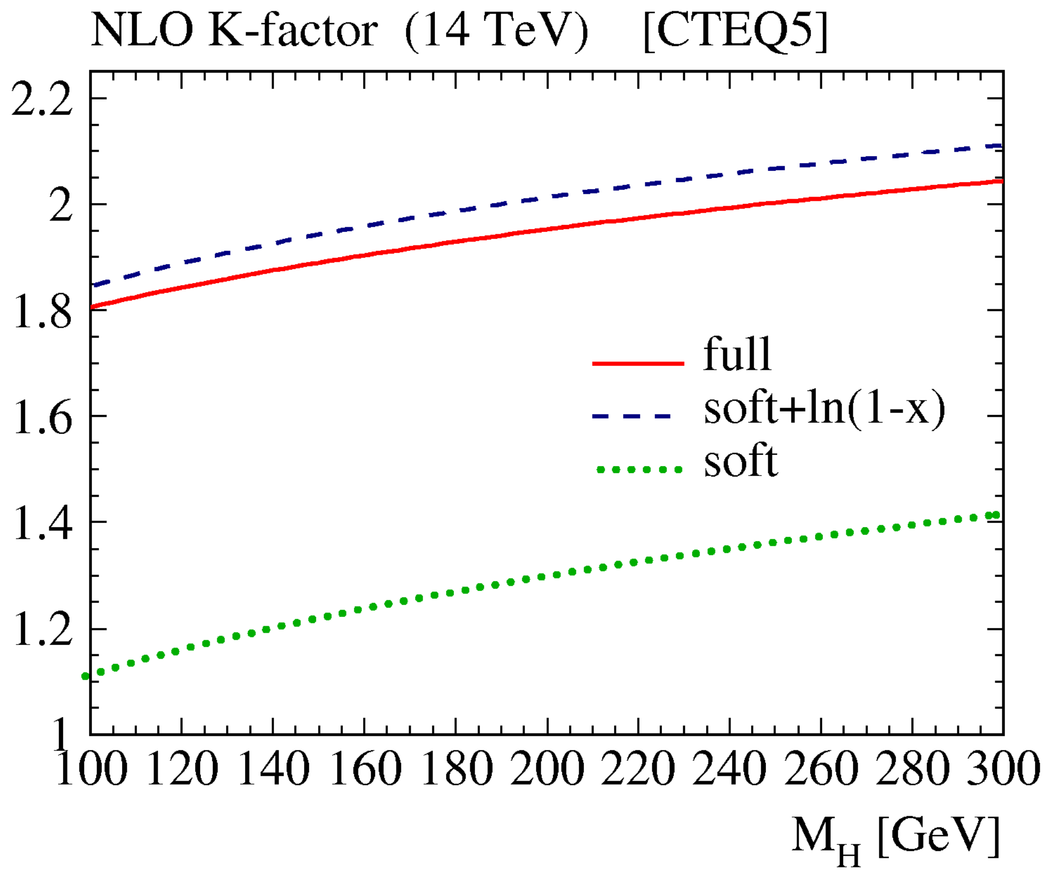
Real emission generates terms like:

$$(1-x)^{-1-m\epsilon} = -\frac{\delta(1-x)}{m\epsilon} + \sum_{n=0}^{\infty} \frac{(-m\epsilon)^n}{n!} \left[\frac{\ln^n(1-x)}{1-x}\right]_+$$

so the $b_k^{(n)}$ terms come for free.

The Soft Limit is not enough!

At NLO, it was found that the soft approximation is inadequate. The leading $c_{lk}^{(n)}$ term dominates!



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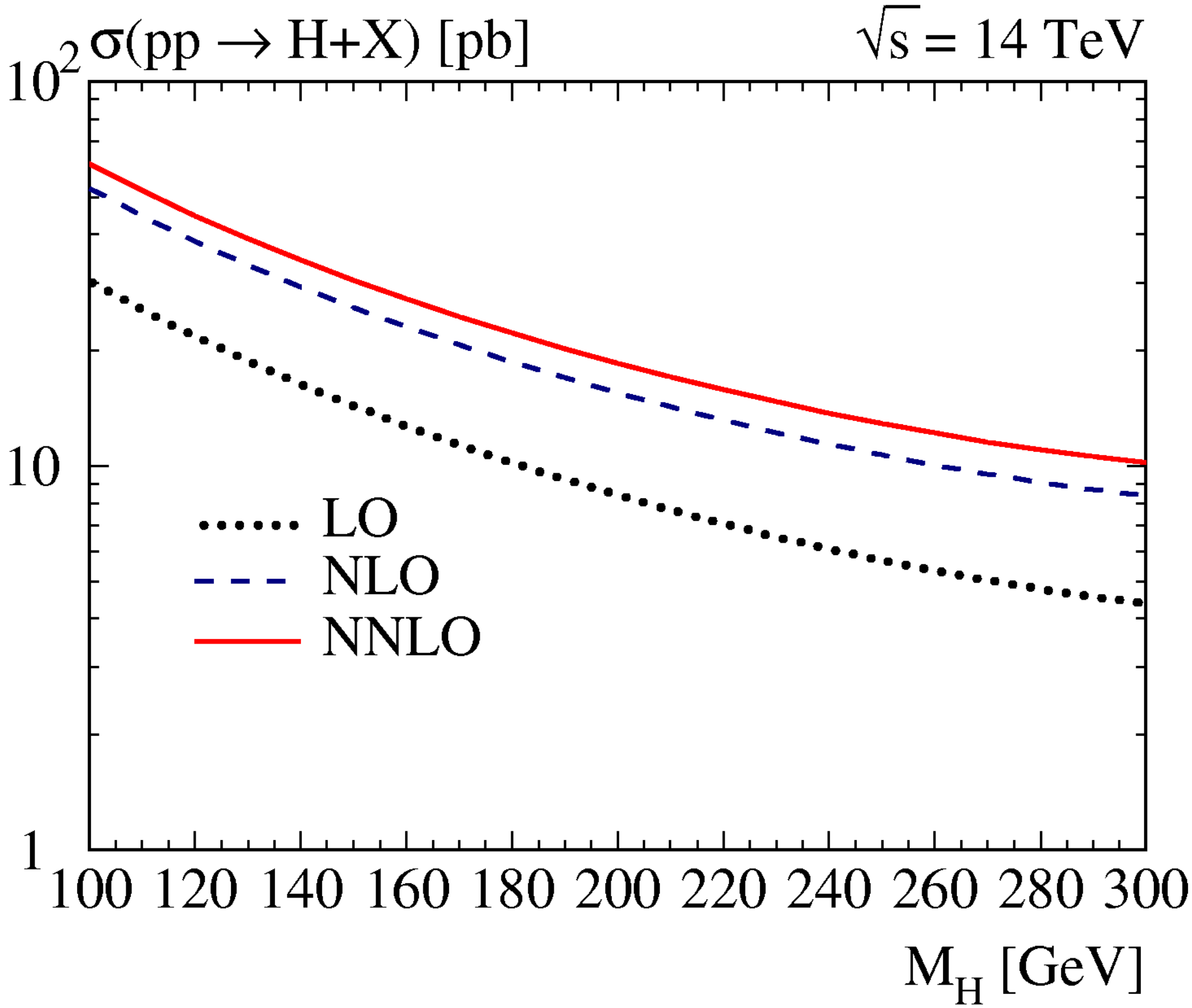
Summing the Series:

With enough terms in the expansion, one can invert the series and obtain the result in closed form if one knows the basis functions:

Prefactors	Functions
$\frac{1}{1-x}$	$1,\ \ln(x)$
$\frac{1}{1+x}$	$\ln^2(x),\ \ln^3(x)$
$\frac{1}{x}$	$\mathrm{Li}_2(1-x),\ \mathrm{Li}_2(1-x)\ln(x)$
1	$\mathrm{Li}_2(1-x^2),\ \mathrm{Li}_2(1-x^2)\ln(x)$
$1-x$	$\mathrm{Li}_3(1-x),\ \mathrm{Li}_3\left(-\frac{1-x}{x}\right)$
$(1-x)^2$	$\mathrm{Li}_3(1-x^2),\ \mathrm{Li}_3\left(-\frac{1-x^2}{x^2}\right)$
$(1-x)^3$	$\mathrm{Li}_3\left(\frac{1-x}{1+x}\right),\ \mathrm{Li}_3\left(-\frac{1-x}{1+x}\right)$

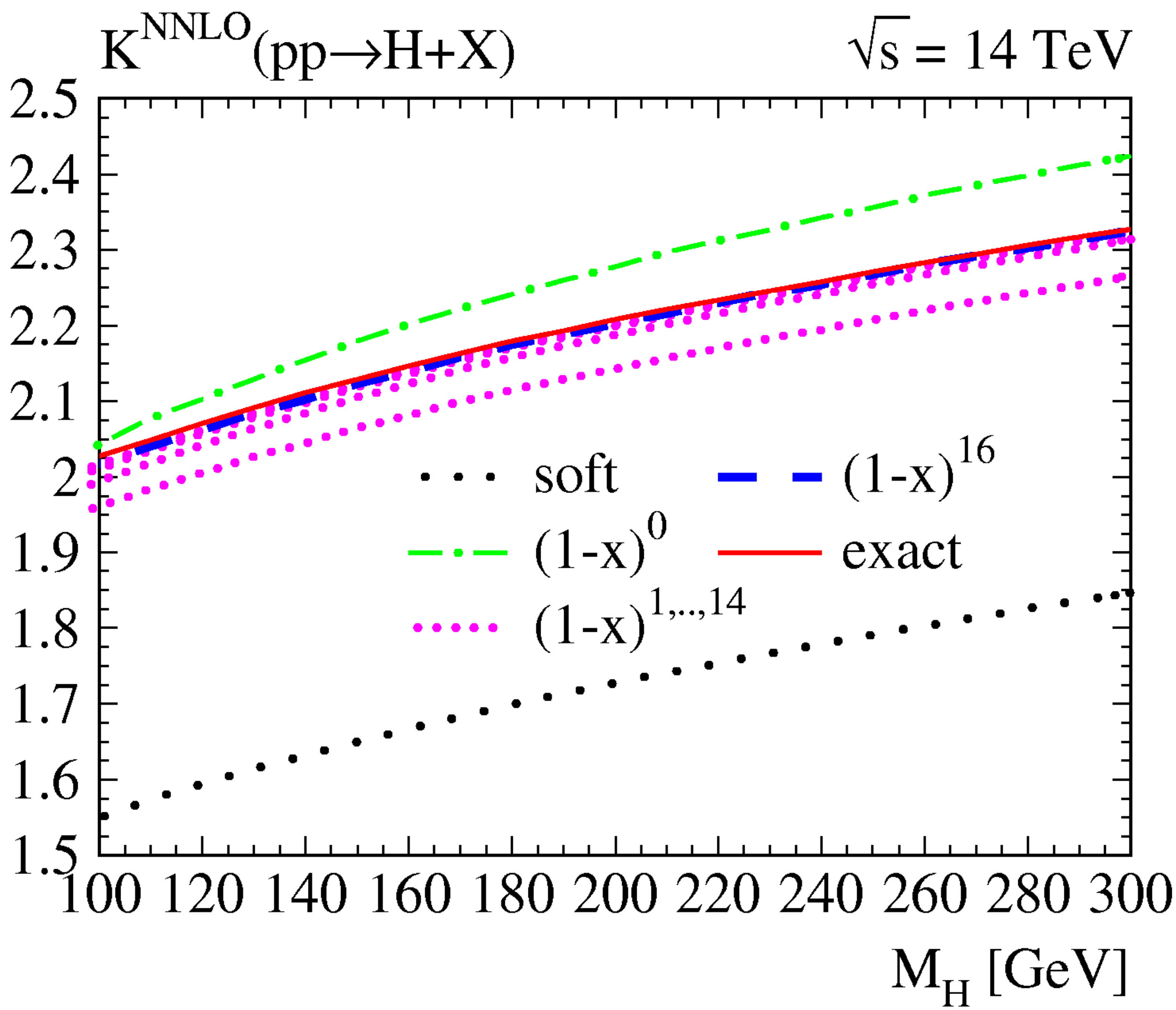
So, with 7x14=98 terms, the series can be inverted.

Results: LHC

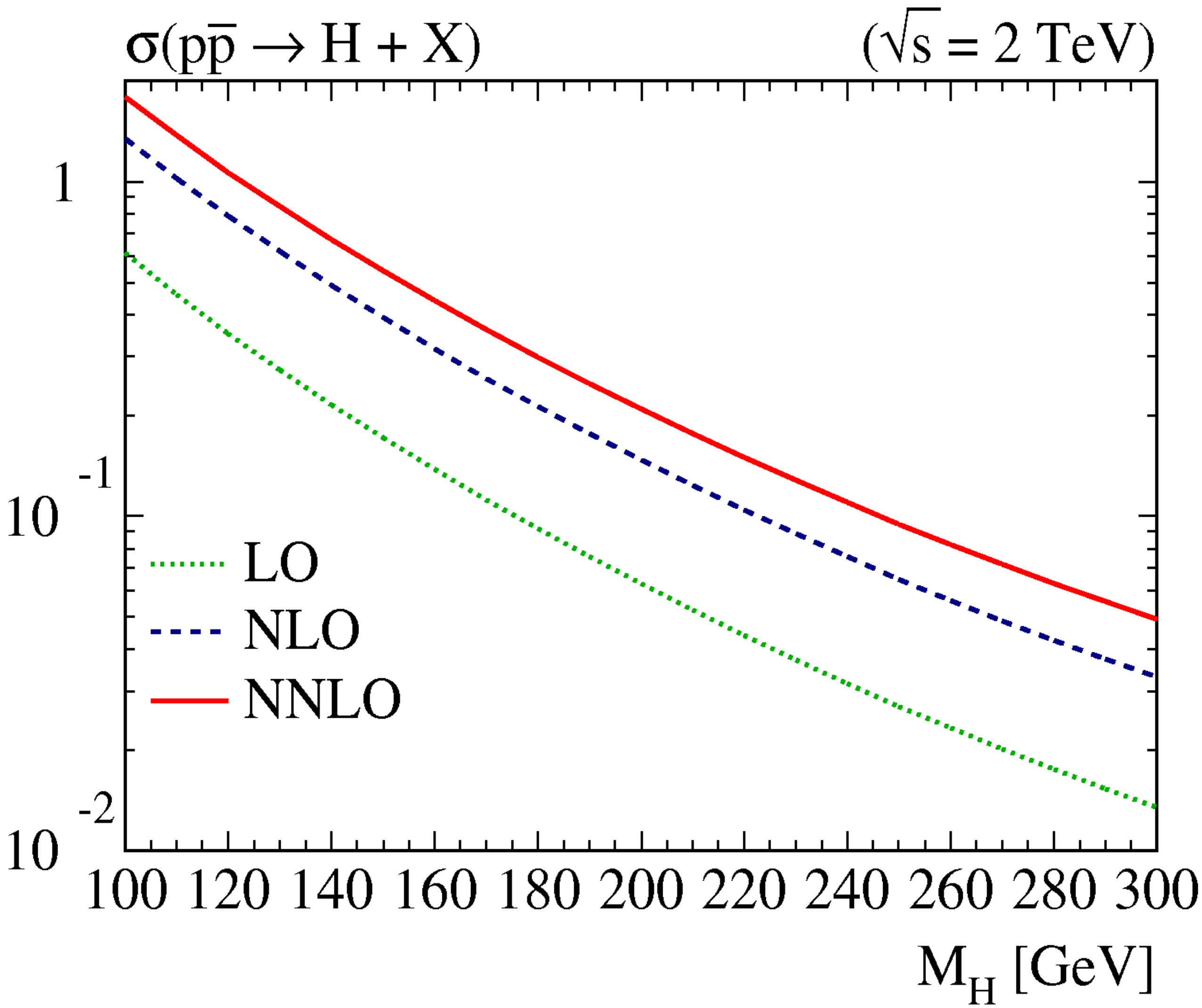


σ(pp → H+X) [pb]
√s = 14 TeV
10^2
10
1
100 120 140 160 180 200 220 240 260 280 300
M_H [GeV]
LO
NLO
NNLO

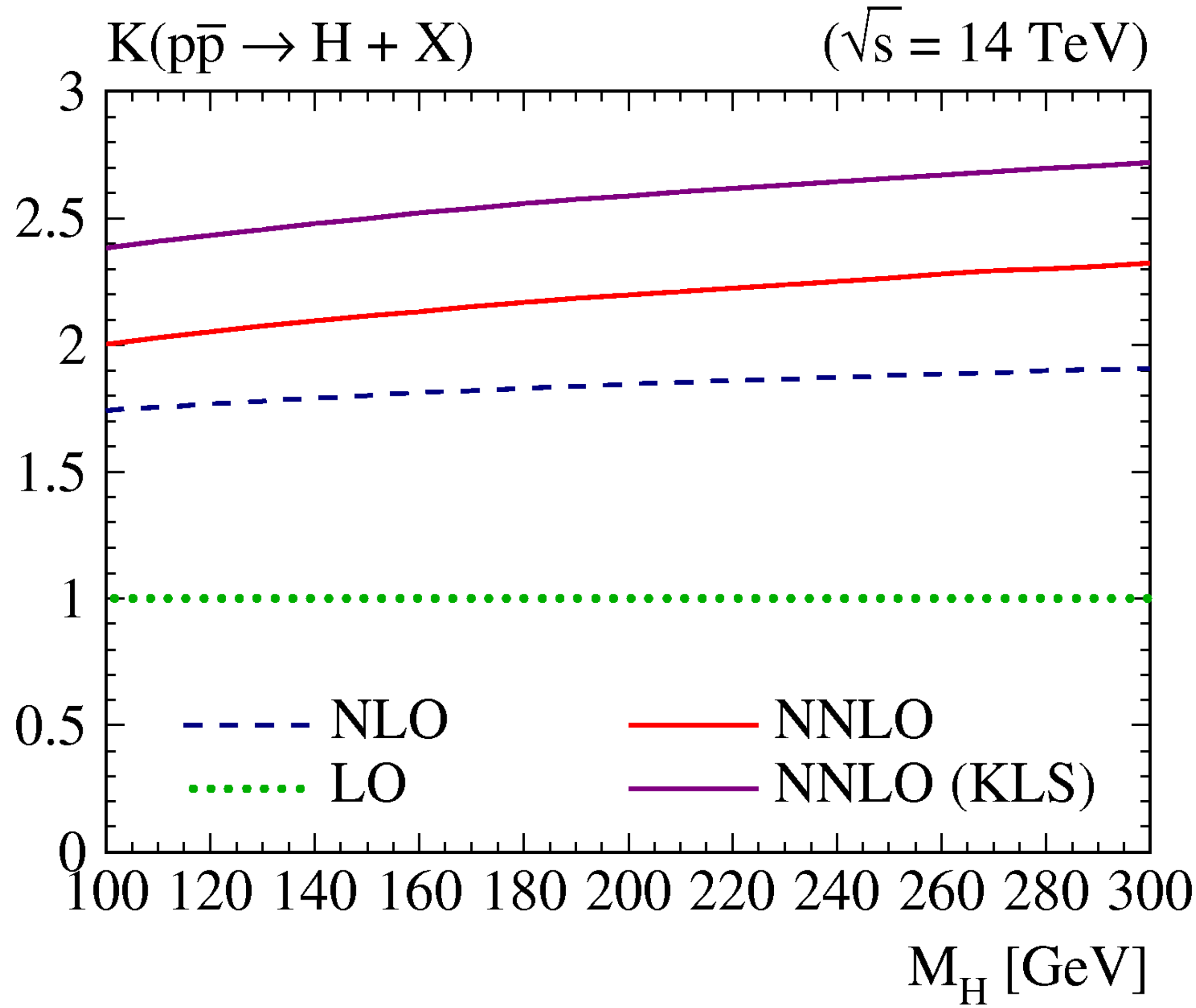
How good is the expansion?
Excellent



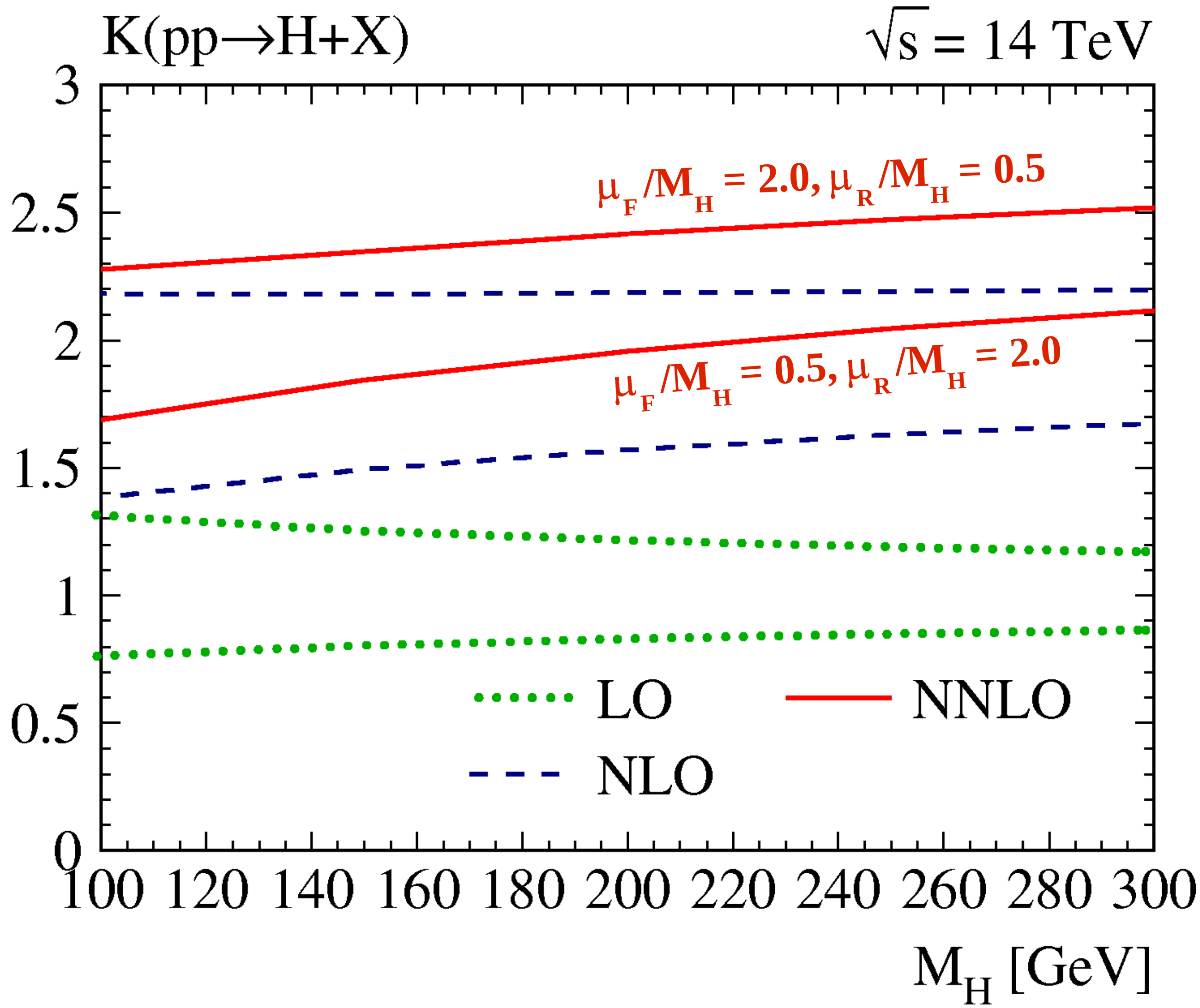
Results: Tevatron



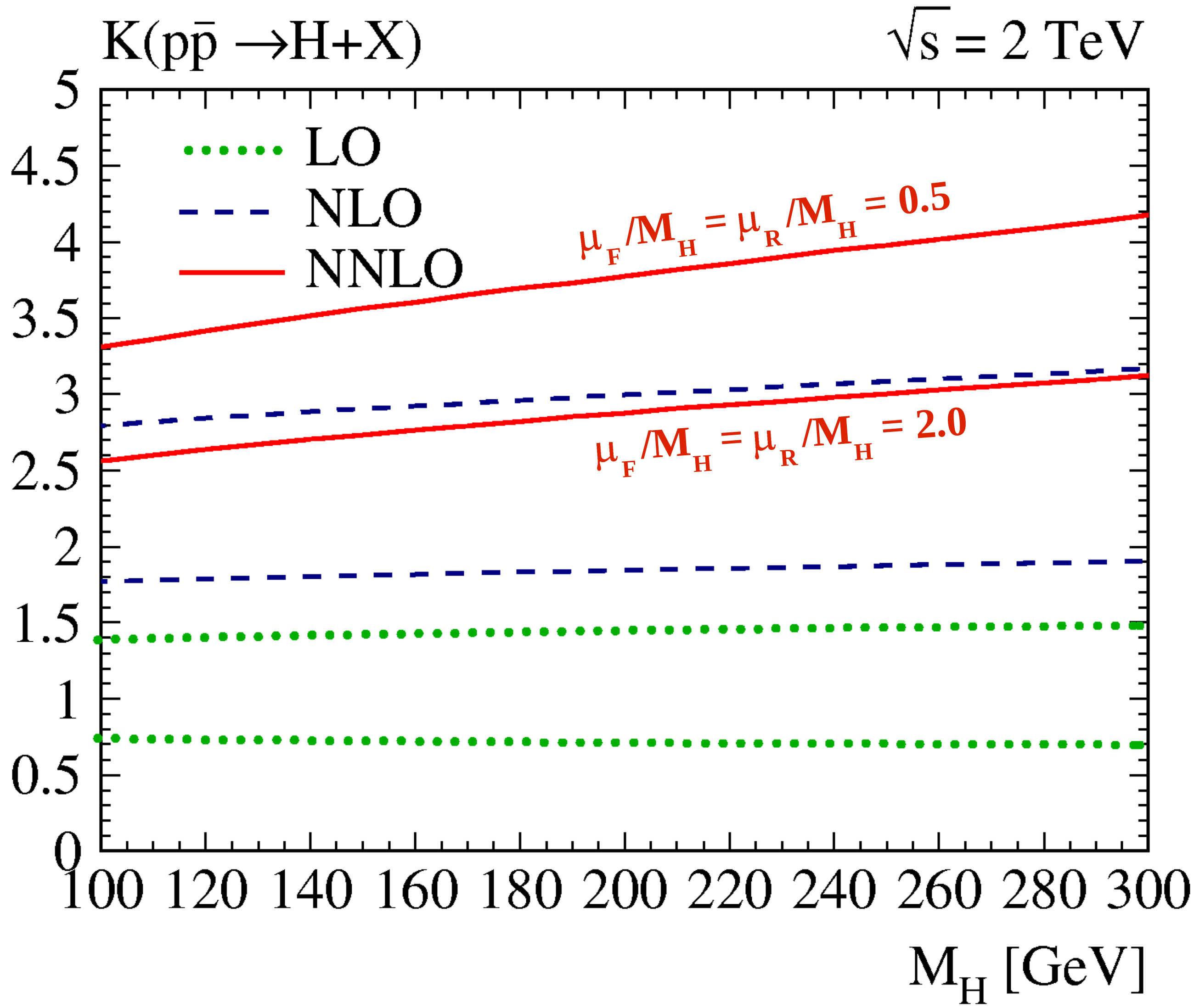
Compare to the predictions of collinear resummation:



Scale Dependence at the LHC



Scale Dependence at the Tevatron



Conclusions

1. We have computed the complete NNLO correction to Inclusive Higgs Boson Production at Hadron Collider in the large M_t limit.
2. The corrections are substantial, but perturbatively well-behaved.
3. Scale Dependence is improved.

This is the first RELIABLE calculation of hadronic Higgs boson production!