Università degli Studi di Milano

INFN Istituto Nazionale di Fisica Nucleare

Impact of the *pdfs* measurements on Higgs production via gluon fusion

Alessandro Vicini
University of Milano, INFN Milano

Torino, November 23rd 2009

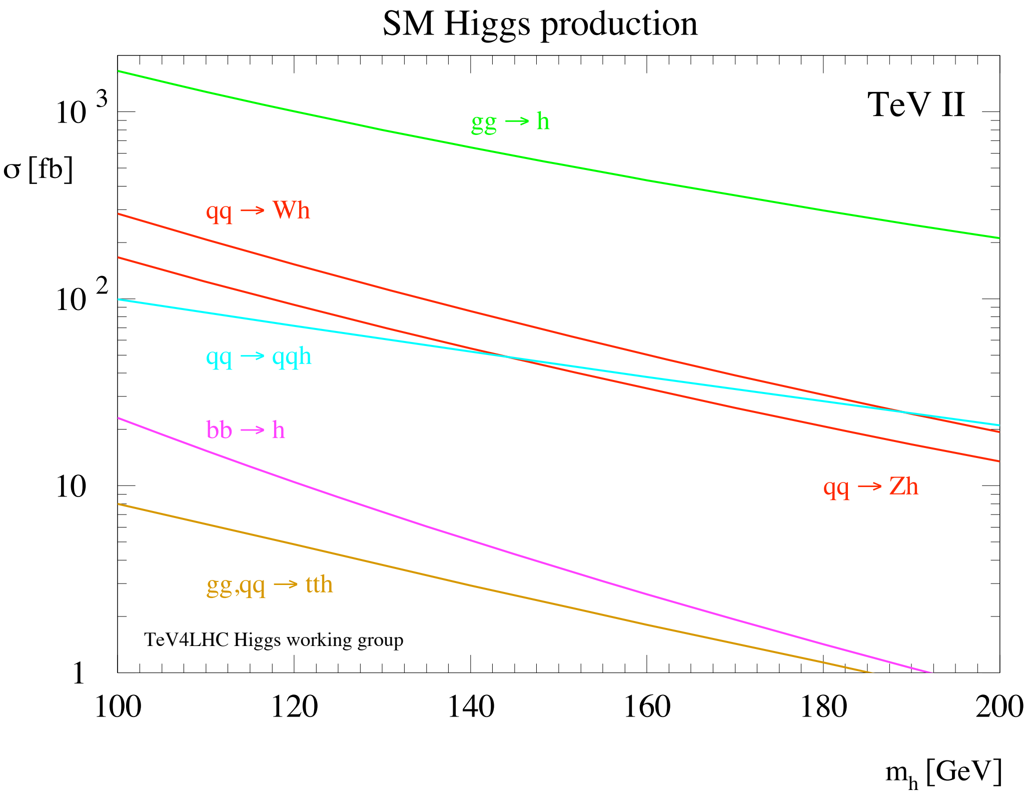
Outline

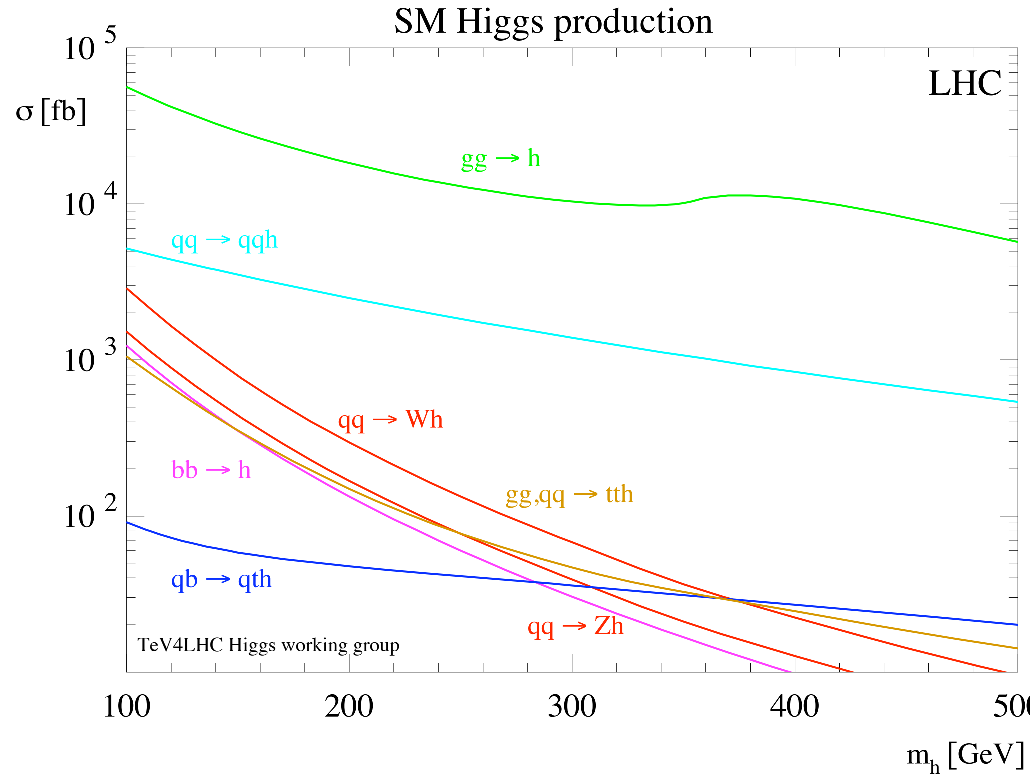
- The gluon fusion Higgs cross section
  (*what we exactly use to prepare the plots*)

- Experimental uncertainties due to: the *pdfs*
  α_s
  m_t

- Theoretical uncertainties: scale variations
  different quark content at NLO

Production mechanisms





The gluon fusion channel is by far the largest production mechanism and requires our best predictions to discover and to study the Higgs boson

Although it starts at 1-loop,
it is enhanced by the large gluon density of the proton

Higgs production

$$\sigma(h_1 + h_2 \to H + X) = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_{a,h_1}(x_1, \mu_F^2) \, f_{b,h_2}(x_2, \mu_F^2) \times$$

$$\times \int_0^1 dz \, \delta\left(z - \frac{\tau_H}{x_1 x_2}\right) \hat{\sigma}_{ab}(z) \, ,$$

proton parton density functions

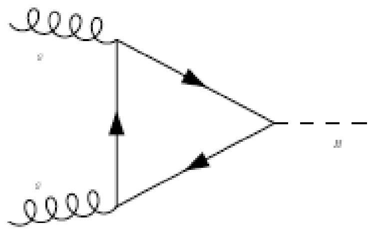
partonic cross sections

According to factorization theorems, the hadronic cross section is written as the convolution of the proton *pdf*s with the partonic cross sections of the relevant parton-parton subprocesses

The partonic cross sections are computed at a given order in QCD

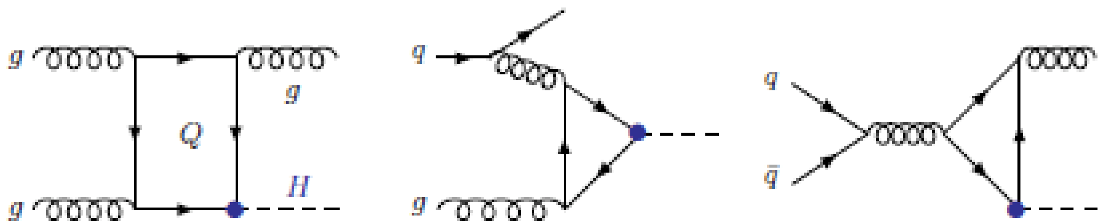
A consistent evaluation of the hadronic cross section requires that:
- -the *pdf*s are extracted with the same accuracy;
- -the strong coupling is evolved with the same accuracy.

Higgs production at NLO-QCD



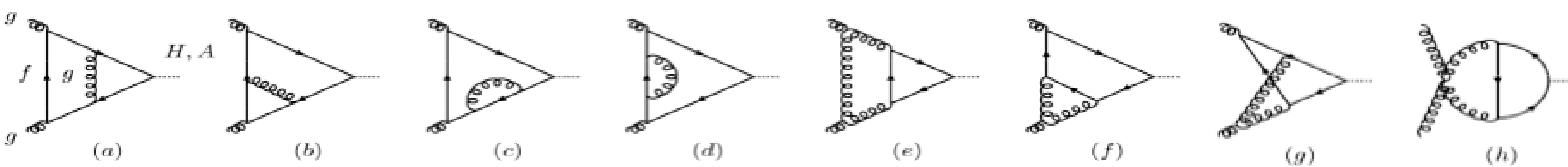
Georgi, Glashow, Machacek, Nanopoulos (1978)

LO



Dawson (1991),
Djouadi, Spira, Zerwas (1991)
Djouadi, Graudenz, Spira, Zerwas (1995)
Harlander, Kant (2005)
Aglietti, Bonciani, Degrassi, Vicini (2007)
Anastasiou, Beerli, Bucherer, Daleo, Kunszt (2007)

NLO-QCD real



NLO-QCD virtual

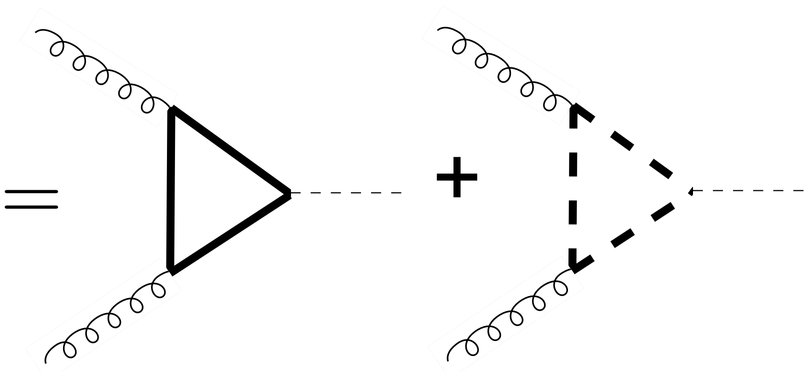
In the fermion loop run all possible quarks

Gluon fusion: NLO-QCD corrections in the SM and beyond

Aglietti, Bonciani Degrassi, AV, JHEP 0701 (2007) 021 JHEP 0711 (2007) 095 program GGSCA

$$\sigma(h_1 + h_2 \to H + X) = \sum_{a,b} \int_0^1 dx_1 dx_2 \; f_a(x_1,\mu_F^2) f_b(x_2,\mu_F^2) \times \int_0^1 dz \delta\left(z - \frac{\tau_H}{x_1 x_2}\right) \; \hat{\sigma}_{ab}(z)$$

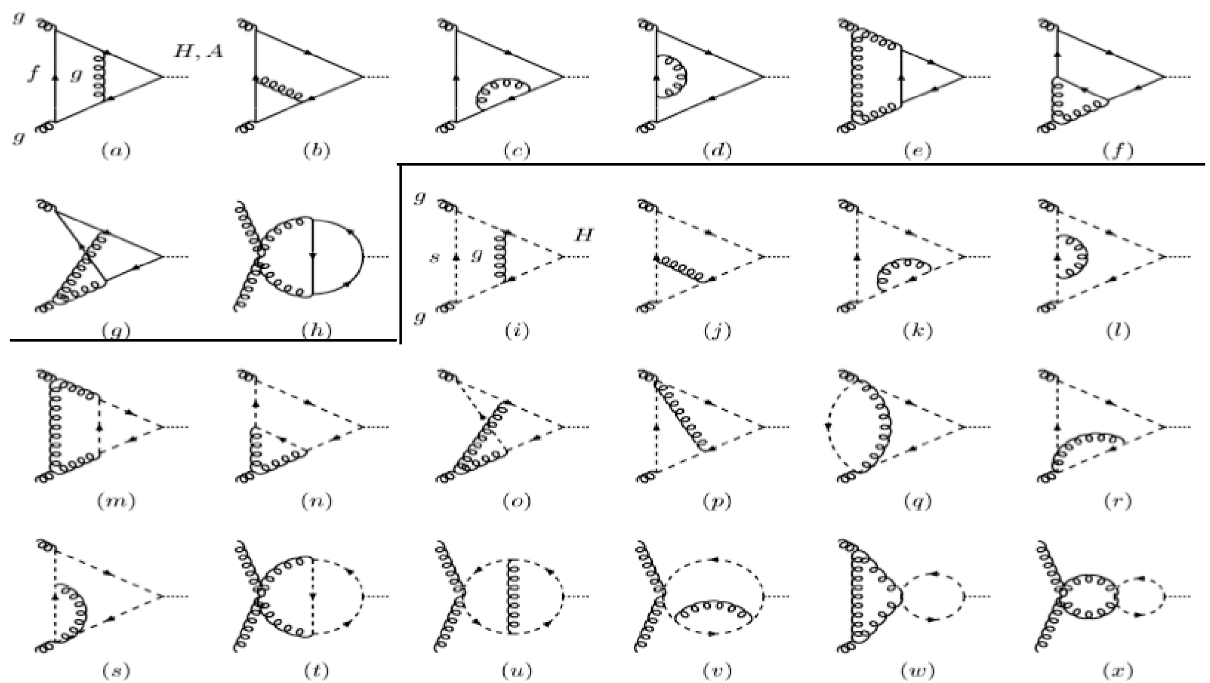
$\mathcal{M} =$



$$\hat{\sigma}_{ab}(z) = \sigma^{(0)} z \; G_{ab}(z)$$

$$\sigma^{(0)} = \frac{G_\mu \alpha_S^2(\mu_R^2)}{128\sqrt{2}\,\pi} \left| \sum_{i=0,1/2} \lambda_i \left(\frac{A^2}{m_0^2}\right)^{1-2i} T(R_i)\, \mathcal{G}_i^{(1l)} \right|^2$$

Gluon fusion: NLO-QCD corrections in the SM and beyond

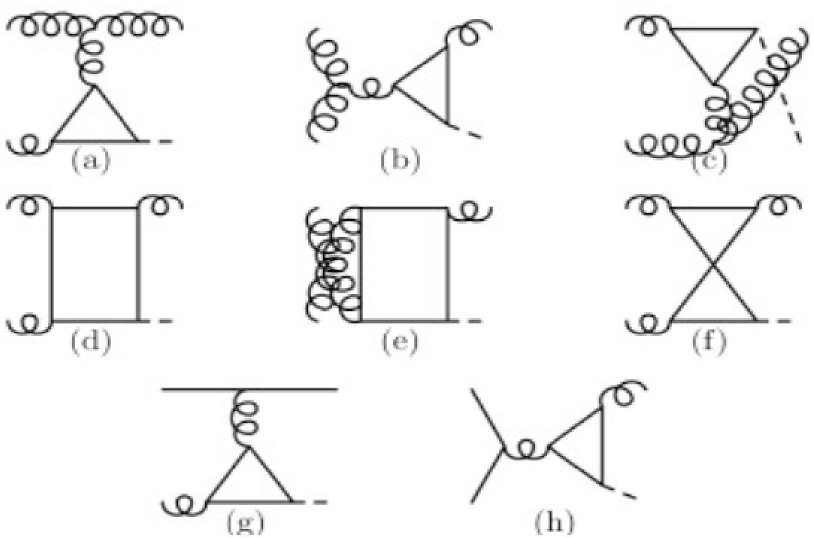


$$\mathcal{G}_i^{(2l)} = \lambda_i \left(\frac{A^2}{m_0^2}\right)^{1-2i} T(R_i)\left(C(R_i)\,\mathcal{G}_i^{(2l,C_R)}(x_i) + C_A\,\mathcal{G}_i^{(2l,C_A)}(x_i)\right)$$

$$\times \left(\sum_{j=0,1/2} \lambda_j \left(\frac{A^2}{m_0^2}\right)^{1-2j} T(R_j)\,\mathcal{G}_j^{(1l)}\right)^{-1} + h.c.$$

Gluon fusion: NLO-QCD corrections in the SM and beyond

Baur, Glover   Ellis, Hincliff, Soldate, van der Bij   Bonciani Degrassi, AV



also all the function A_ij expressed in terms of HPLs

$$\mathcal{R}_{gg} = \frac{1}{z(1-z)} \int_0^1 \frac{dv}{v(1-v)} \left\{ \frac{8\, z^4 \left|\mathcal{A}_{gg}(\hat{s},\hat{t},\hat{u})\right|^2}{\left|\sum_{j=0,1/2} \lambda_j \left(\frac{A^2}{m_0^2}\right)^{1-2j} T(R_j)\, \mathcal{G}_j^{(1l)}\right|^2} - (1-z+z^2)^2 \right\}$$

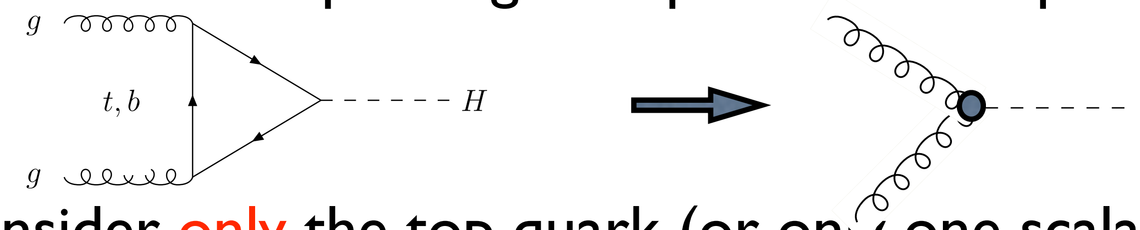
$$\mathcal{R}_{q\bar{q}} = \frac{128}{27} \frac{z\,(1-z)\, \left|\mathcal{A}_{q\bar{q}}(\hat{s},\hat{t},\hat{u})\right|^2}{\left|\sum_{j=0,1/2} \lambda_j \left(\frac{A^2}{m_0^2}\right)^{1-2j} T(R_j)\, \mathcal{G}_j^{(1l)}\right|^2}$$

$$\mathcal{R}_{qg} = C_F \int_0^1 \frac{dv}{(1-v)} \left\{ \frac{1+(1-z)^2 v^2}{[1-(1-z)v]^2} \frac{2\, z \left|\mathcal{A}_{qg}(\hat{s},\hat{t},\hat{u})\right|^2}{\left|\sum_{j=0,1/2} \lambda_j \left(\frac{A^2}{m_0^2}\right)^{1-2j} T(R_j)\, \mathcal{G}_j^{(1l)}\right|^2} - \frac{1+(1-z)^2}{2z} \right\} + \frac{1}{2} C_F z$$

QCD K-factor and the large-mt limit

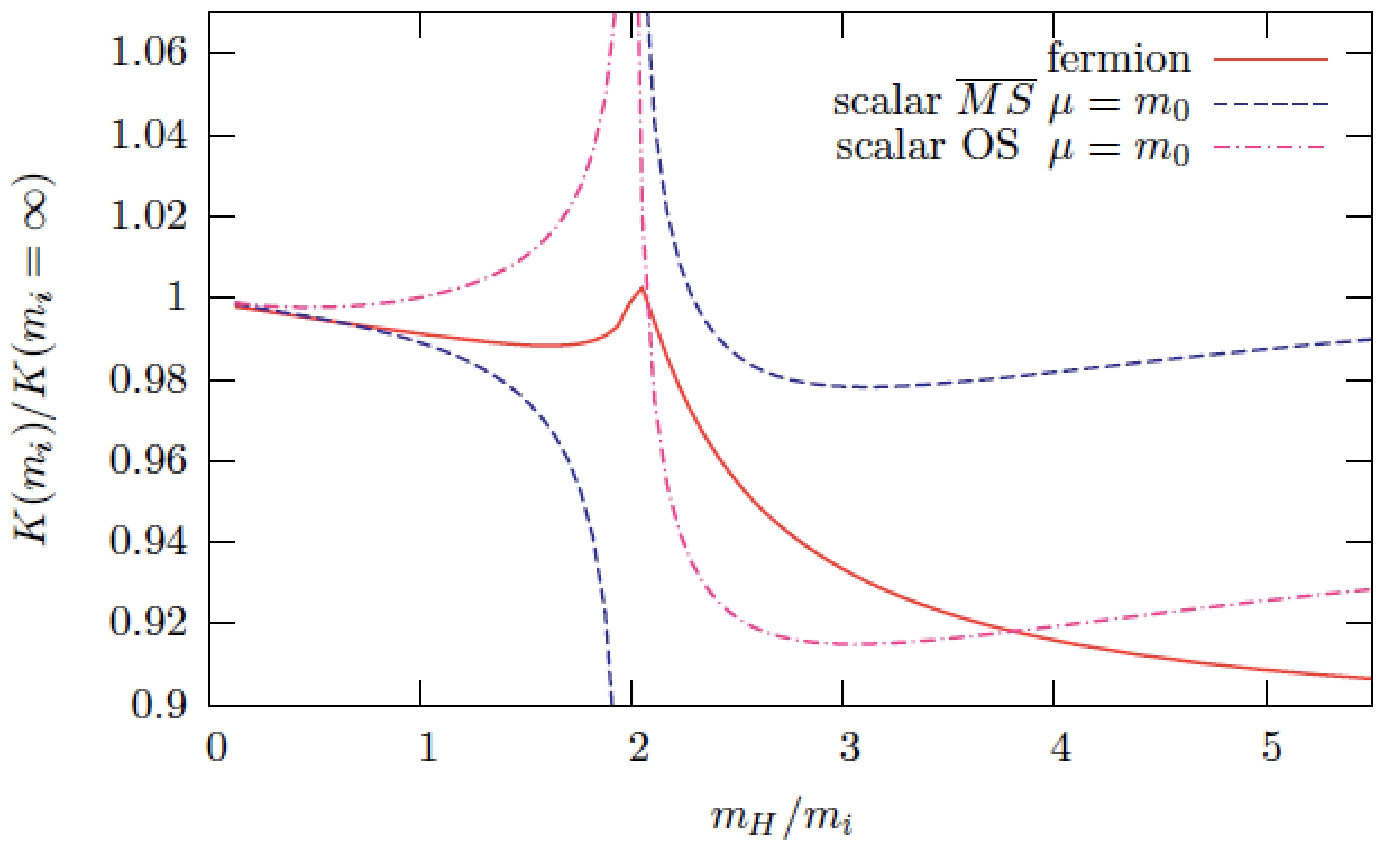
Bonciani Degrassi, AV

large-mt limit: the top triangle loop shrinks to a pointlike interaction vertex



if we consider only the top quark (or only one scalar) in the loop,
then the K-factor in the large-mt limit is already a good approximation of the exact K-factor

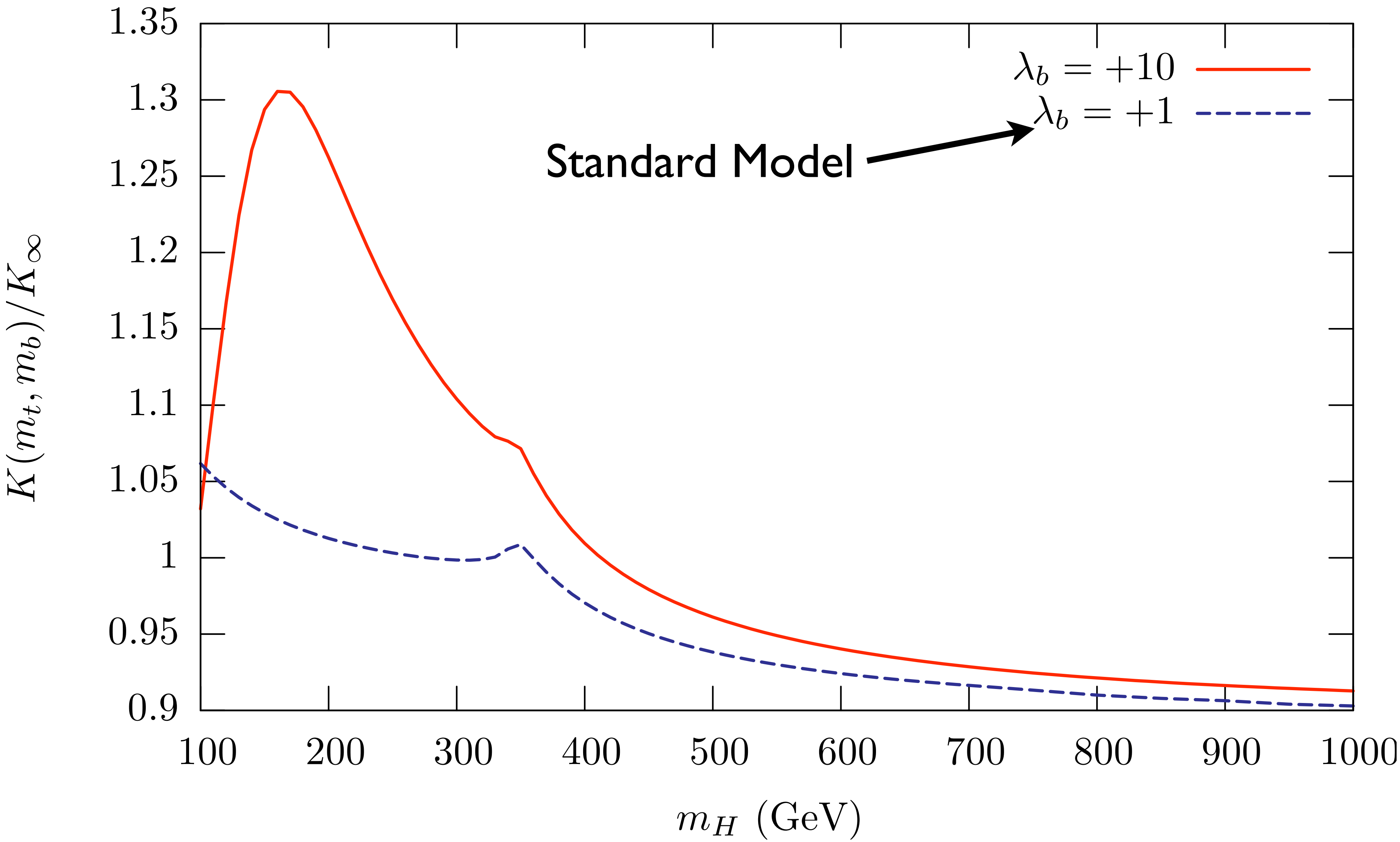
but we have to include at least also the bottom!



Exact QCD K-factor

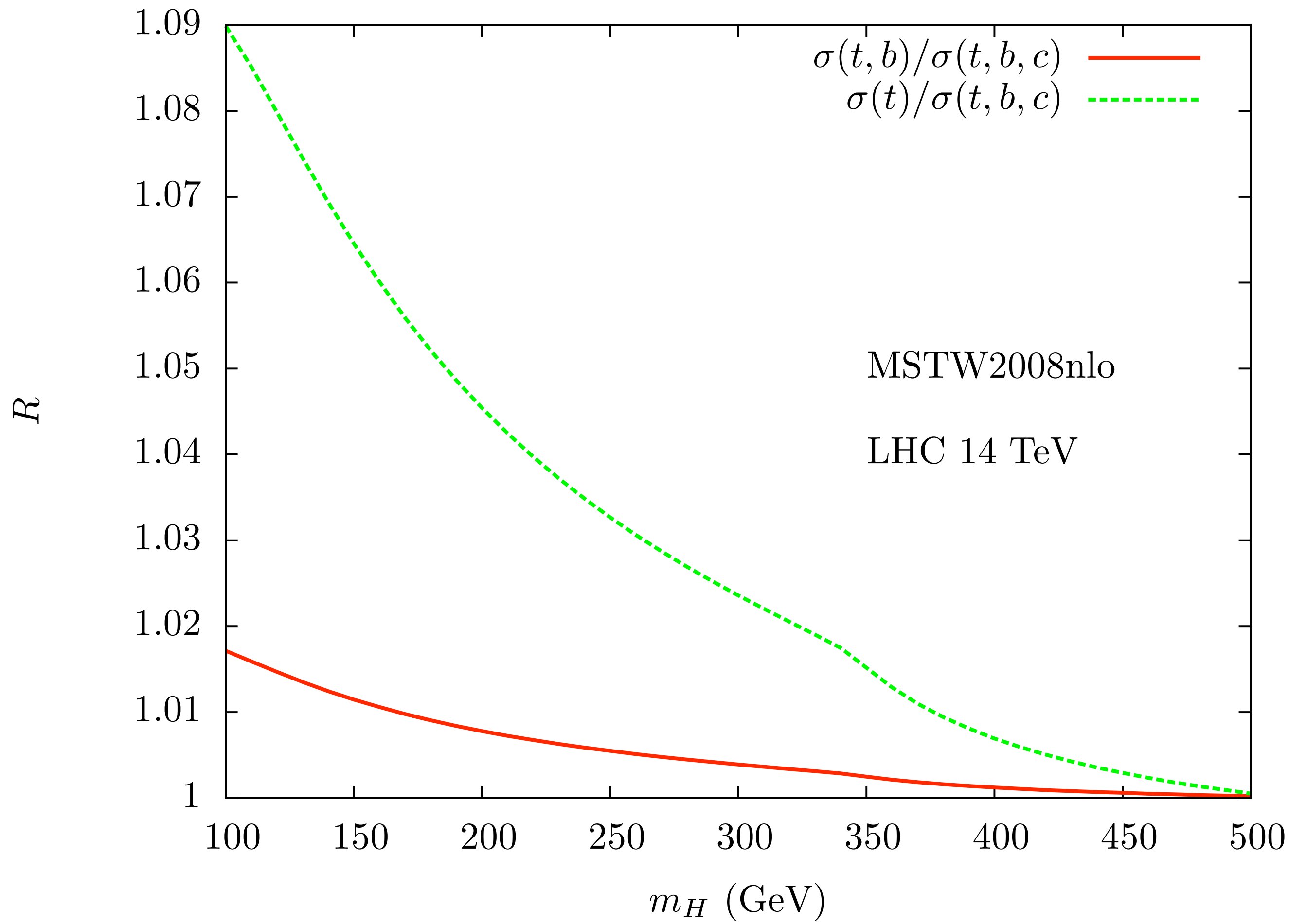
Bonciani Degrassi, AV

➔ if we include QCD corrections to the light particles in the loop
the K-factor in the exact calculation may differ from the approximated one



also at NLO non trivial interferences between
the top and bottom (and charm, strange,...) amplitudes

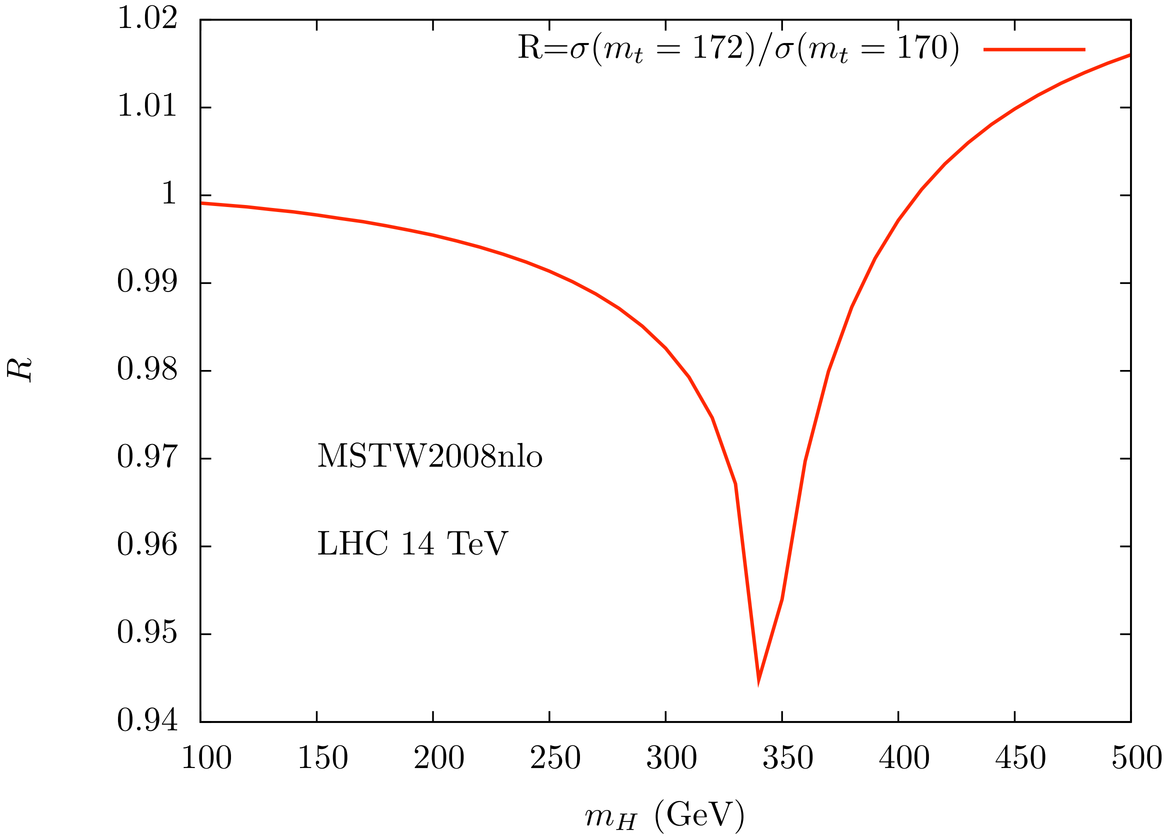
Effects of the inclusion of the amplitude with the charm quark



Alike the bottom, also the charm quark has a negative effect on the cross section because of a negative interference effect between top and charm amplitudes

All these ingredients are available since 1995 in HIGLU
(very good numerical agreement of our code with HIGLU)!

m_t dependence



For light Higgs, dependence on the precise value of the top mass below 0.5%

Around and above the ttbar threshold, non trivial dependence

Higgs production beyond NLO-QCD

- NNLO-QCD results in the $m_t \to \infty$ limit (+15%)

  Anastasiou, Melnikov (2002), Harlander,Kilgore (2002)
- finite mt effects at NNLO-QCD (~ 0.5 %)

  Marzani, Ball, Del Duca, Forte, Vicini (2008) Harlander, Ozeren (2009)
- soft-gluon resummation at NNLL-QCD (+ 6%)

  Catani, De Florian, Grazzini, Nason (2003)
- inclusion of leading NNNLO-QCD contributions (+ 5%)

  Moch, Vogt (2005)
- full NLO-EW corrections (+4-7 %)

  Aglietti, Bonciani, Degrassi, Vicini (2004,2005) Actis, Passarino, Sturm, Uccirati (2007,2008), Keung,Petriello (2009)

Further increase , beyond NLO-QCD,of the total cross section:

+25-30% of the Born

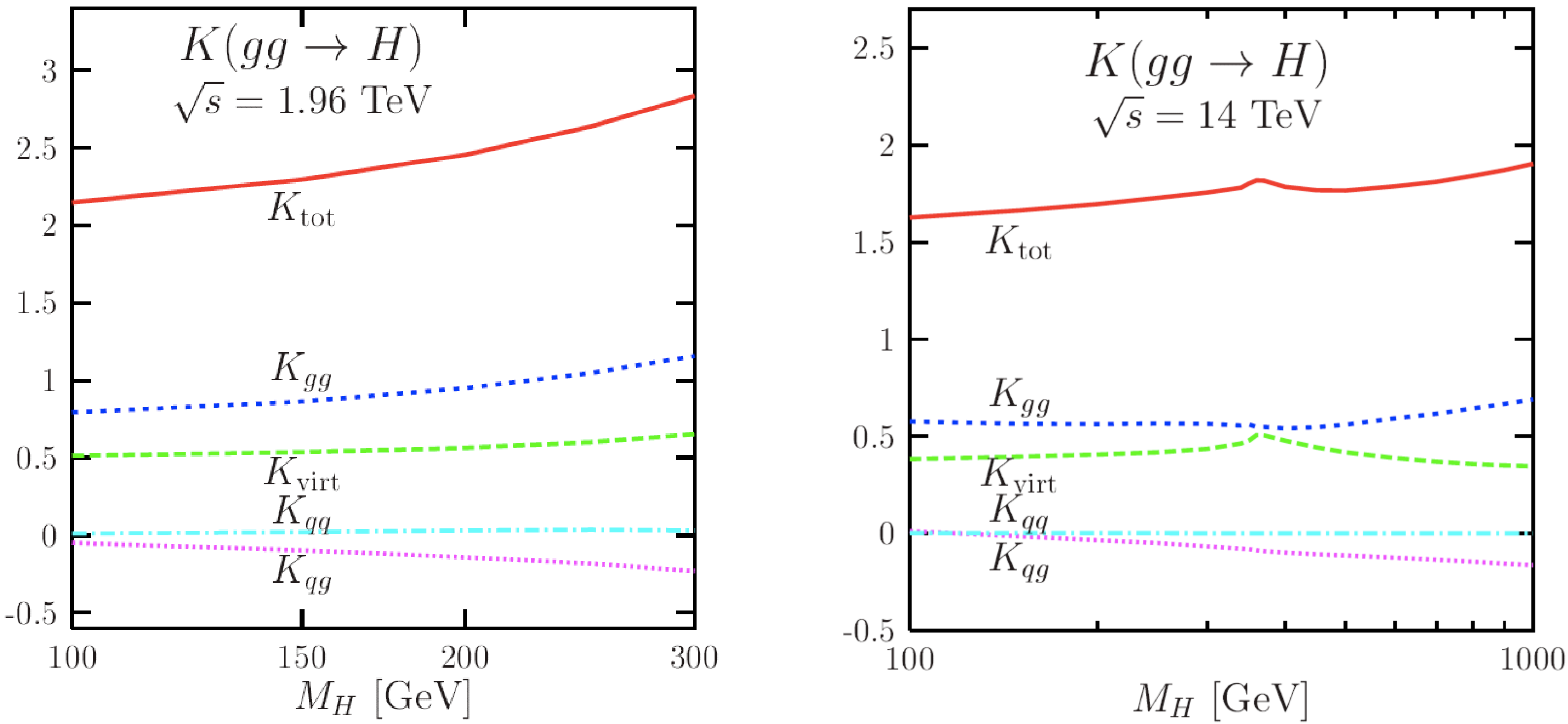
Stability against renormalization/factorization scale variation

Good accuracy of the partonic cross section

➔ In this talk I will mostly discuss NLO-QCD results where *pdf*s can be compared

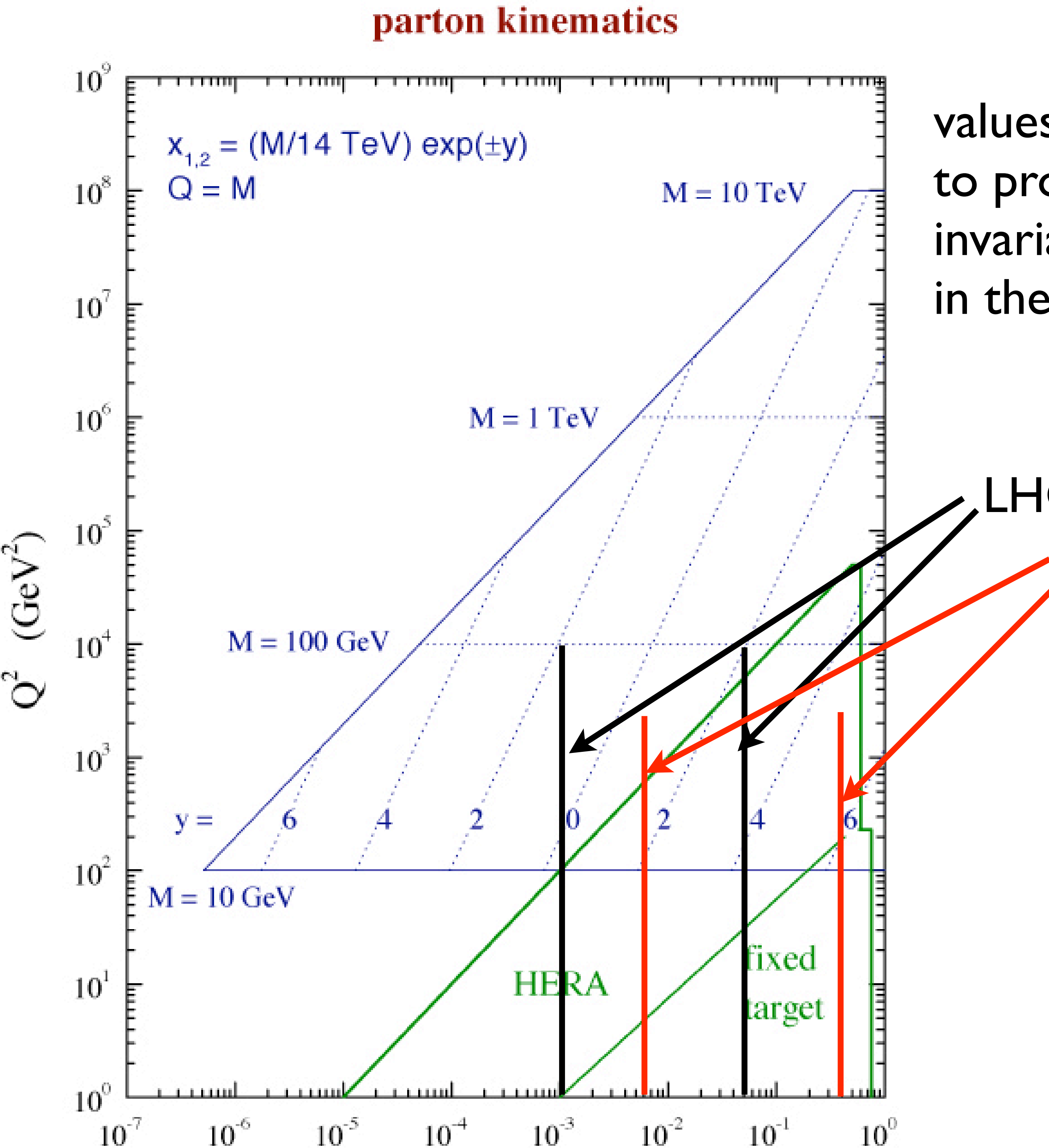
extraction from the data of *pdf*s with NNLO-QCD accuracy would require the use of full set (unavailable) of NNLO-QCD calculations

Higgs production at NLO-QCD



The gluon subprocesses
(both real and virtual)
give the largest contribution
to the total cross-section

Need to reduce the uncertainty
on the gluon pdf



values of *x* relevant
to produce a final state with
invariant mass of 100 GeV
in the central rapidity interval

$$|y_H| \leq 2$$

LHC [0.00096, 0.052]

Tevatron [0.0069, 0.376]

Kinematics

The small-*x* region plays a minor role in the evaluation of the inclusive cross section (dominated by lowest-order threshold kinematics)

Cross section dominated by the lowest order partonic threshold kinematics
Large contribution due to soft gluon emission at the threshold
One small-*x* value in one pdf requires a large-*x* value in the other, but the steep fall of the gluon density suppresses these contributions

→ The uncertainties associated to the small-*x* region do not affect the total cross section

Differences of the gluon density in the large-*x* region, due e.g. to different treatment of jet data, may appear at intermediate *x* because normalization/ momentum sum rules constraints

Higgs production at NLO-QCD: *pdfs* uncertainties

The uncertainty due to the experimental errors of the data, from which the *pdfs* are extracted, is parametrized in different ways:

- Montecarlo replicas
- Hessian method

The corresponding definitions to compute the standard deviation associated to an observable $\mathcal{F}$ is

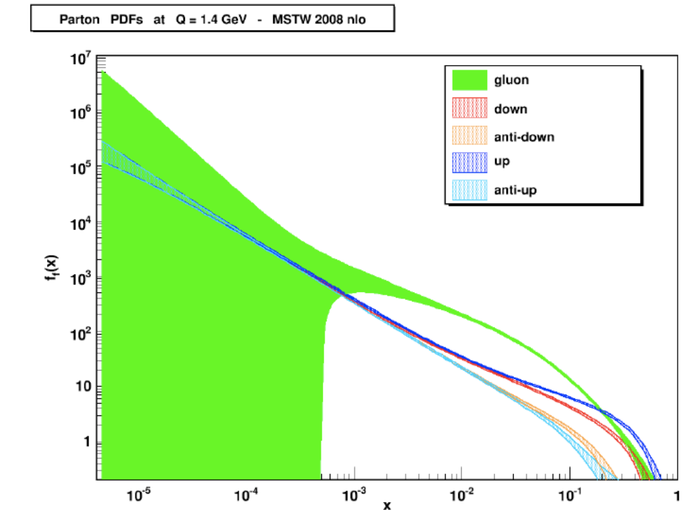
$$\sigma_{\mathcal{F}} = \left(\frac{1}{N_{\rm set}-1} \sum_{k=1}^{N_{\rm set}} \left(\mathcal{F}[\{q^{(k)}\}] - \langle \mathcal{F}[\{q\}] \rangle \right)^2 \right)^{1/2}$$

$$\sigma_{\mathcal{F}}^{\rm hepdata} = \frac{1}{2C_{90}} \left(\sum_{k=1}^{N_{\rm set}/2} \left(\mathcal{F}[\{q^{(2k-1)}\}] - \mathcal{F}[\{q^{(2k)}\}] \right)^2 \right)^{1/2}$$

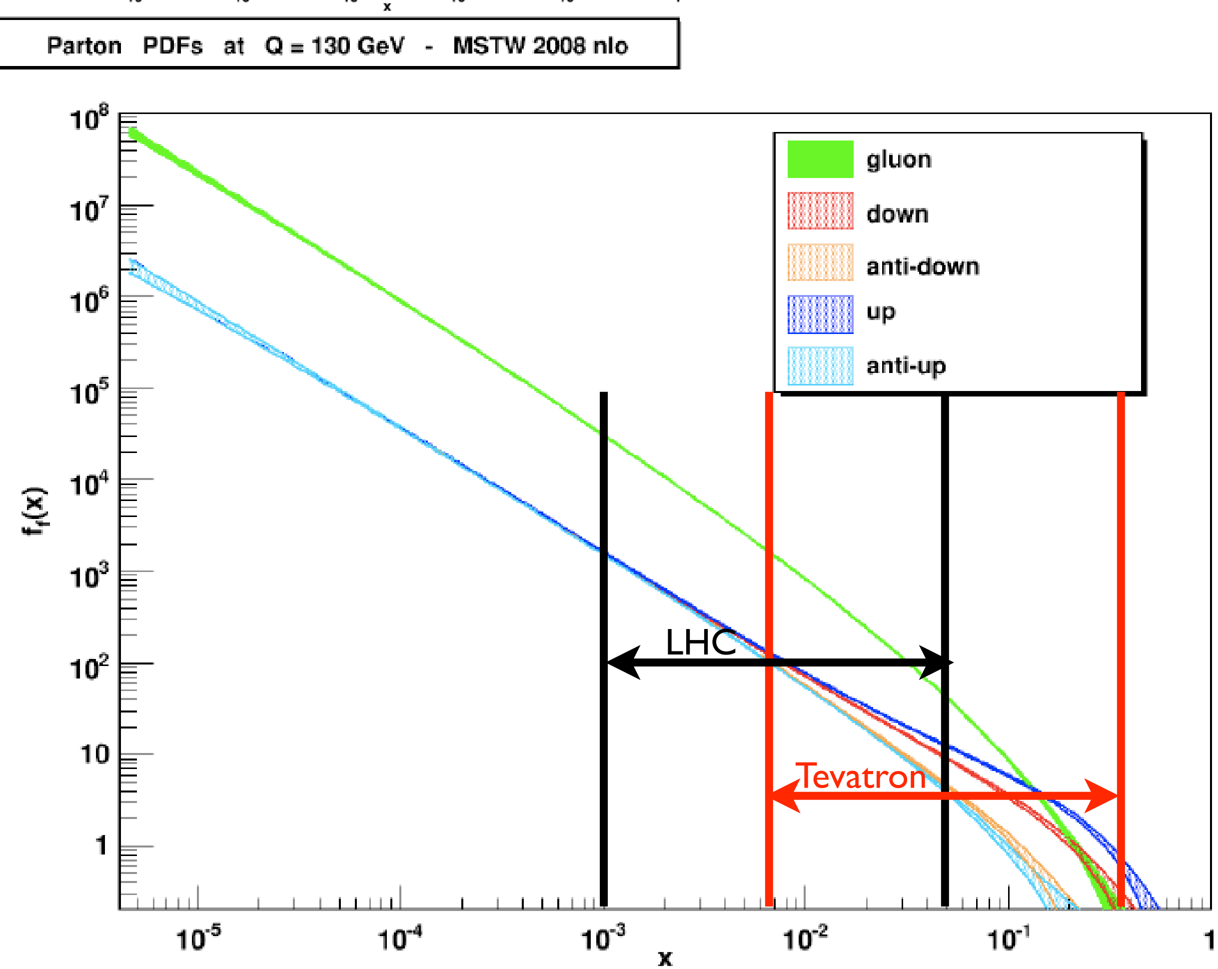
The factor C_90 is not necessary any more for MSTW2008, where differents sets are provided, which parametrize the uncertainties at 68% and at 90% C.L.

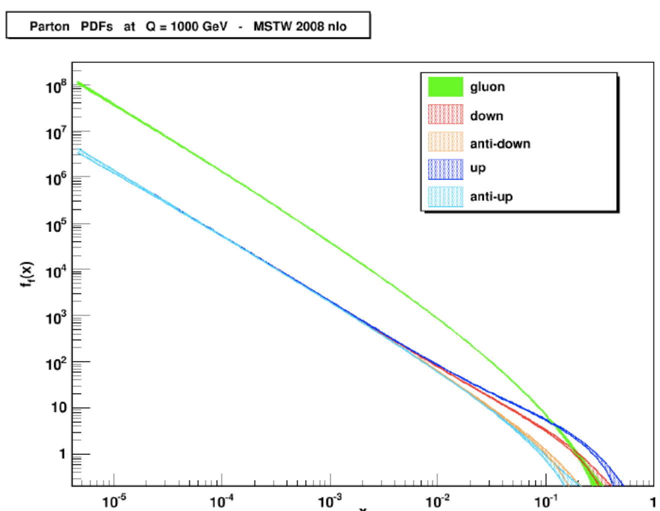
In our exercise $\mathcal{F}$ is: the inclusive Higgs production cross section at NLO-QCD the parton densities

Effects of Altarelli-Parisi evolution



the *x* relevant for the gluon fusion are well measured at HERA





Comparison of *pdfs*

CTEQ6.6

DIS data, DY data, jets at colliders (not included: Tevatron run II, NuTeV, CHORUS data)
the data are fitted with a functional form fixed a priori
propagation of experimental errors to the *pdf*s described using the Hessian method

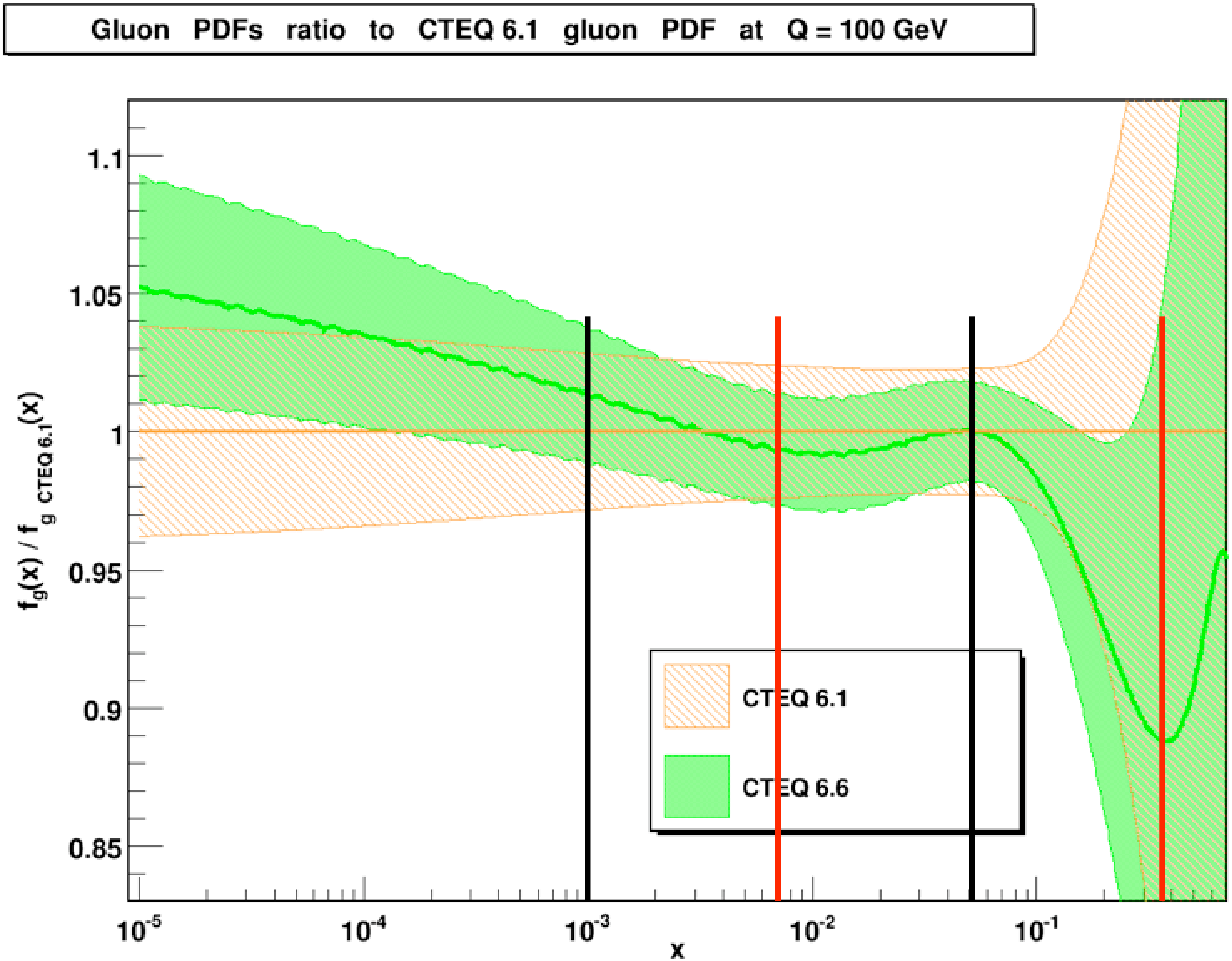
MSTW2008

DIS data, DY data, jets at colliders
the data are fitted with a functional form fixed a priori
propagation of experimental errors to the *pdf*s described using the Hessian method

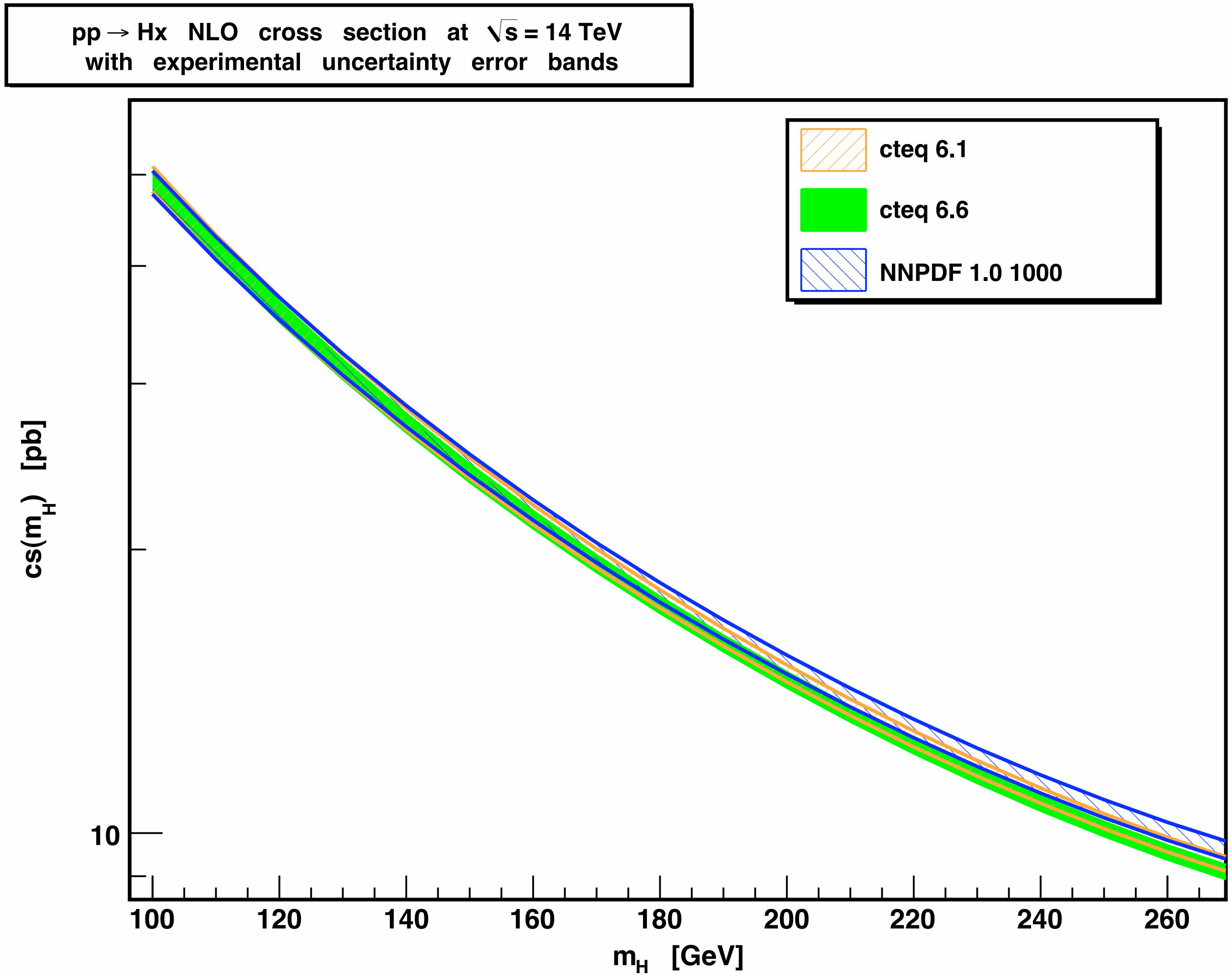
NNPDF1.2

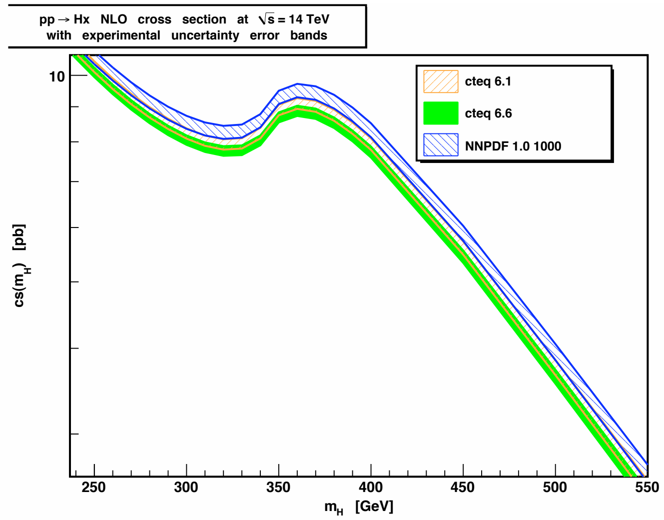
only DIS scattering data (NC and CC)
MC replicas of the data are generated within the experimental error
a Neural Network learns from the replicas a possible parametrization of the *pdf*s
the final set of pdfs provides a sampling of the *pdf*s parameter space
and allows to measure, in a statistically meaningful way, the spread of any observable
not yet full treatment of heavy quarks

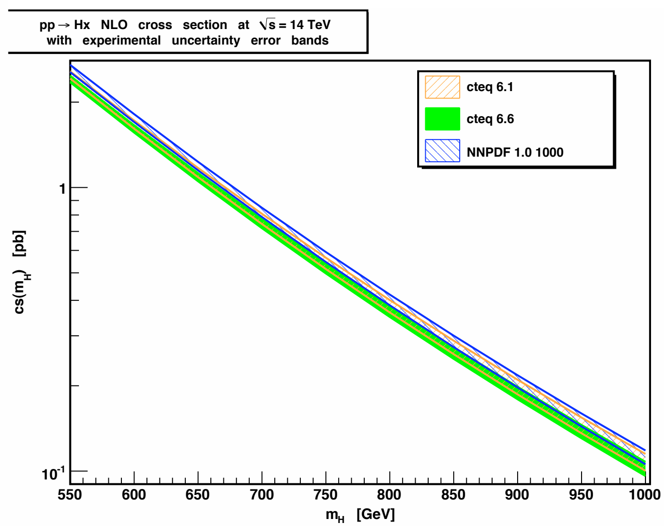
CTEQ gluon densities



Higgs production at NLO-QCD: changes using CTEQ *pdfs*

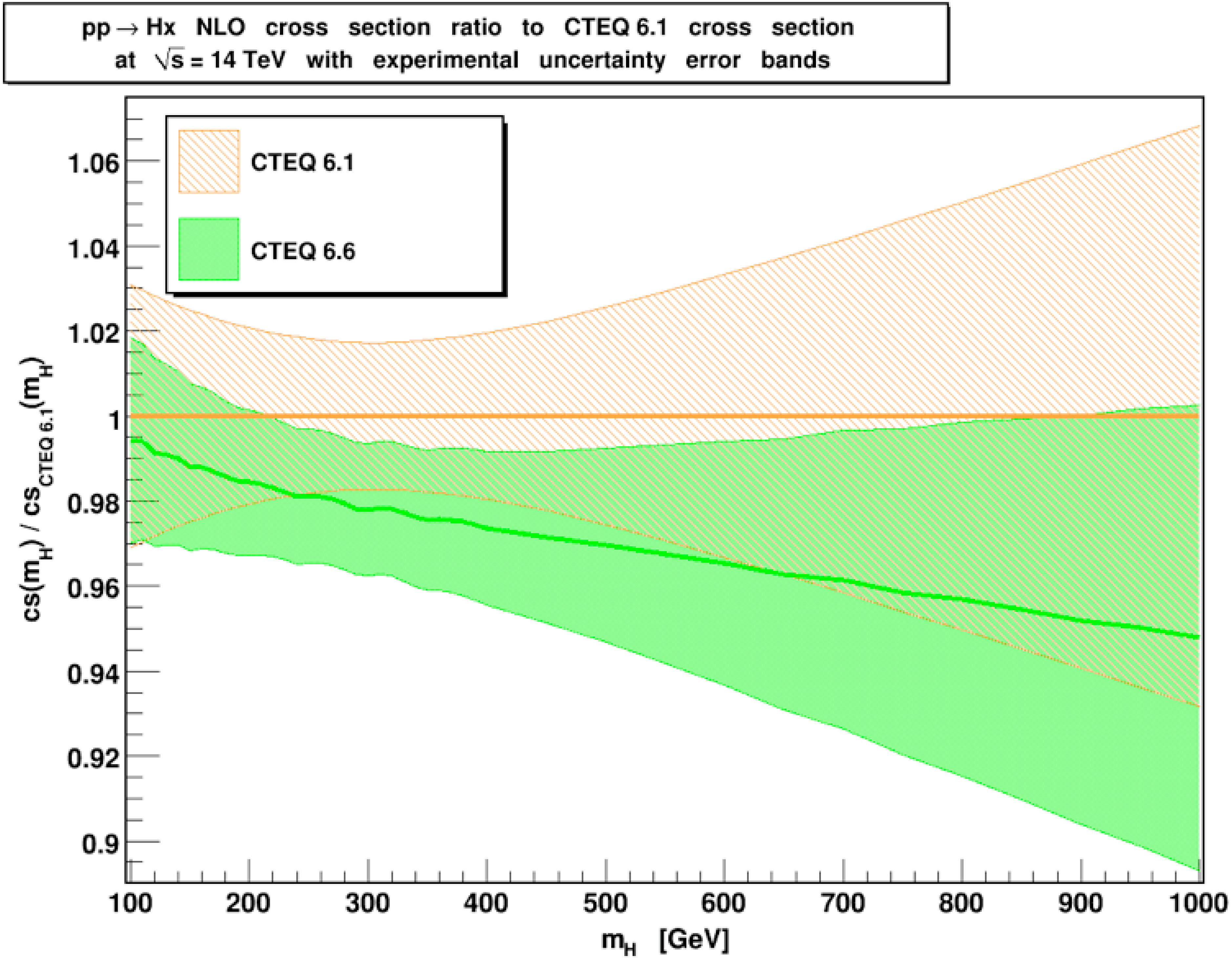




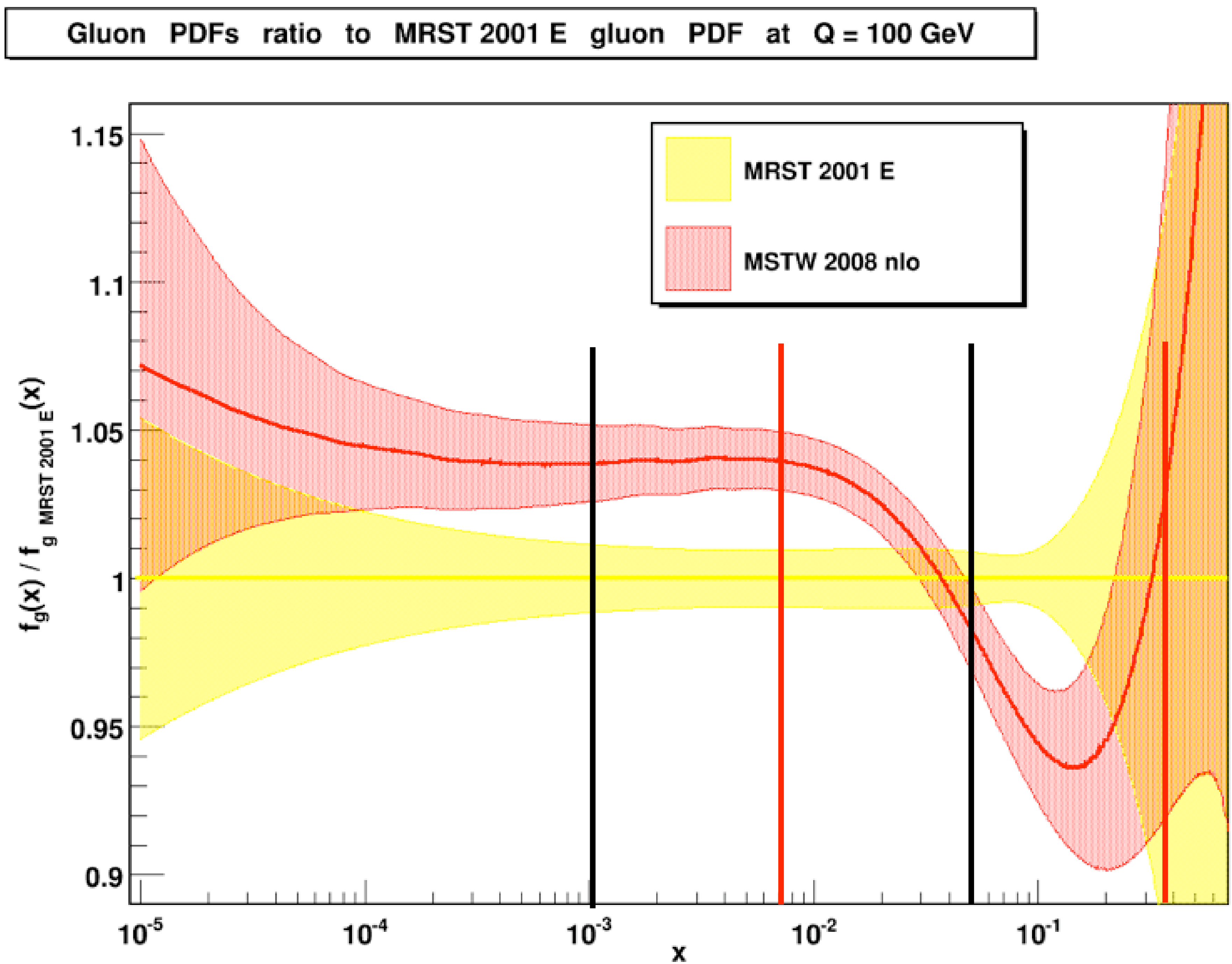


larger changes for large MH

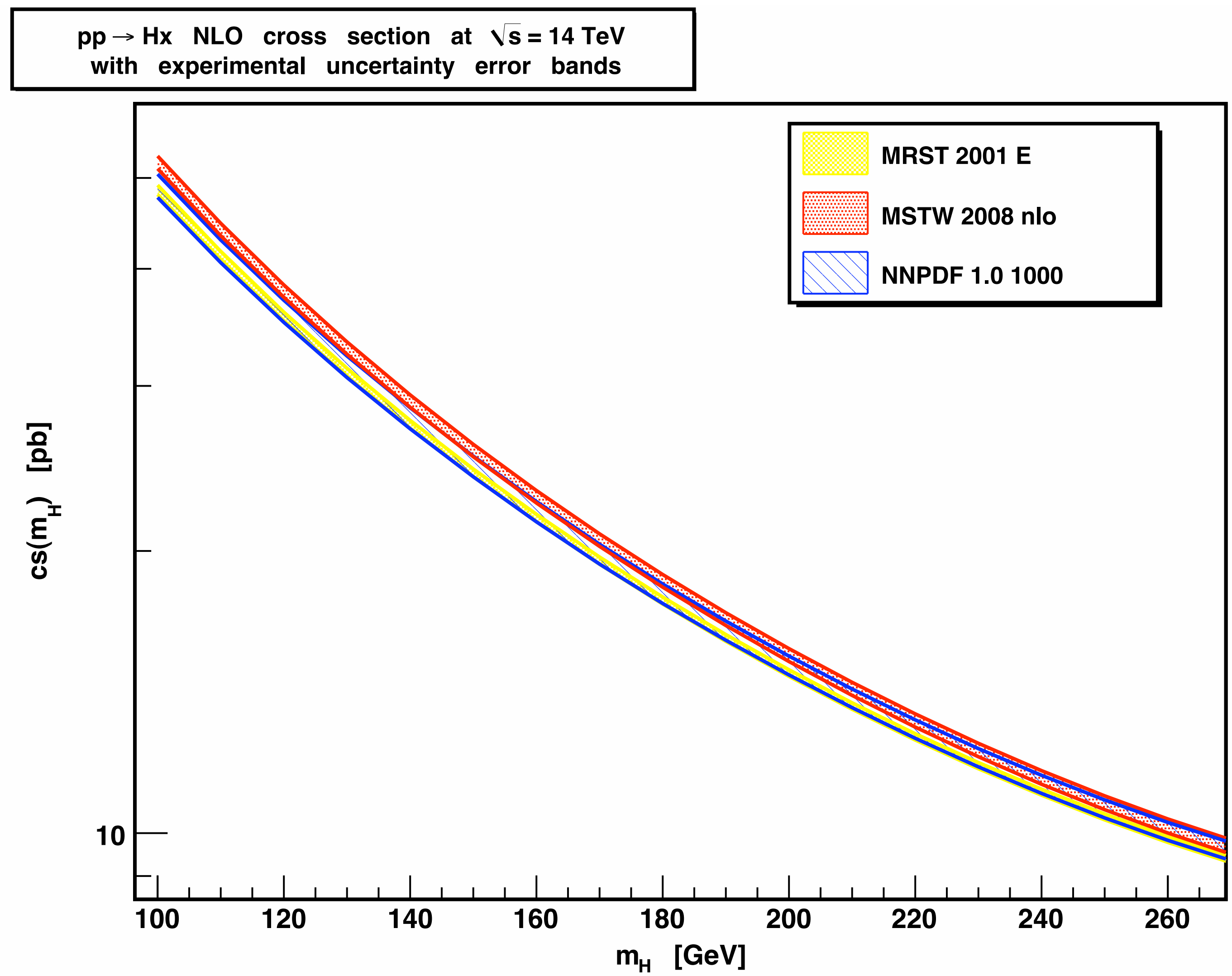
CTEQ cross sections

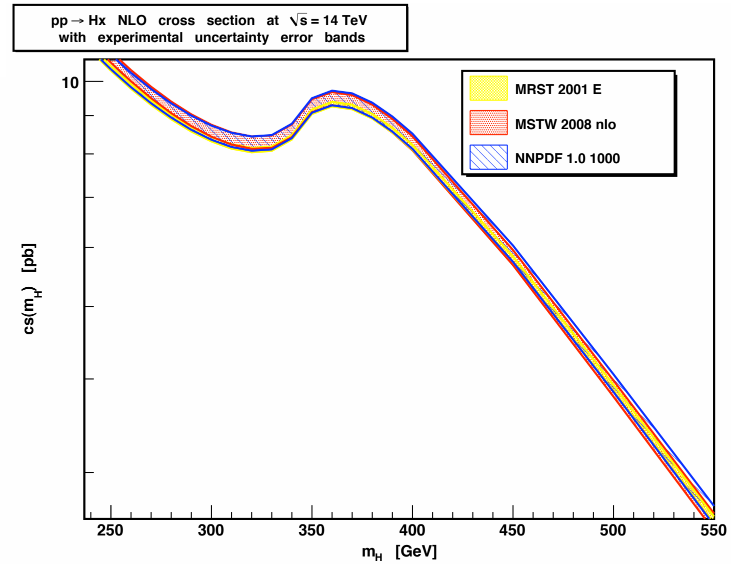


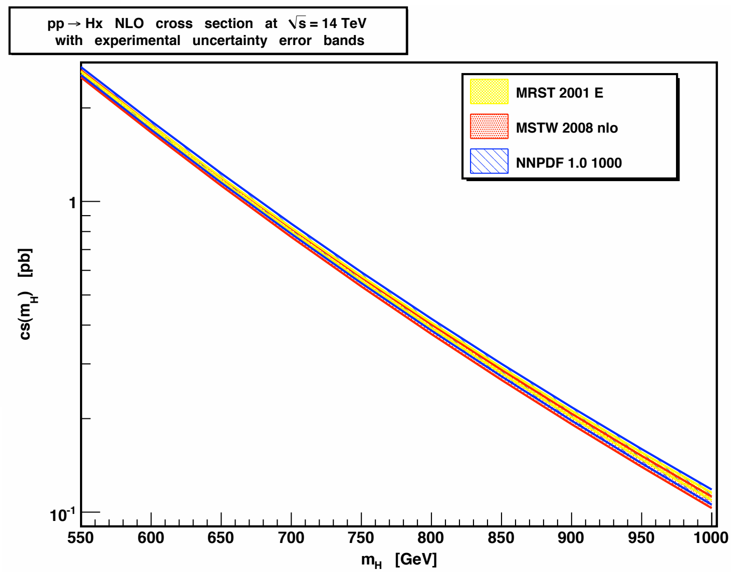
MSTW gluon densities



Higgs production at NLO-QCD: changes using M(R)ST(W) sets

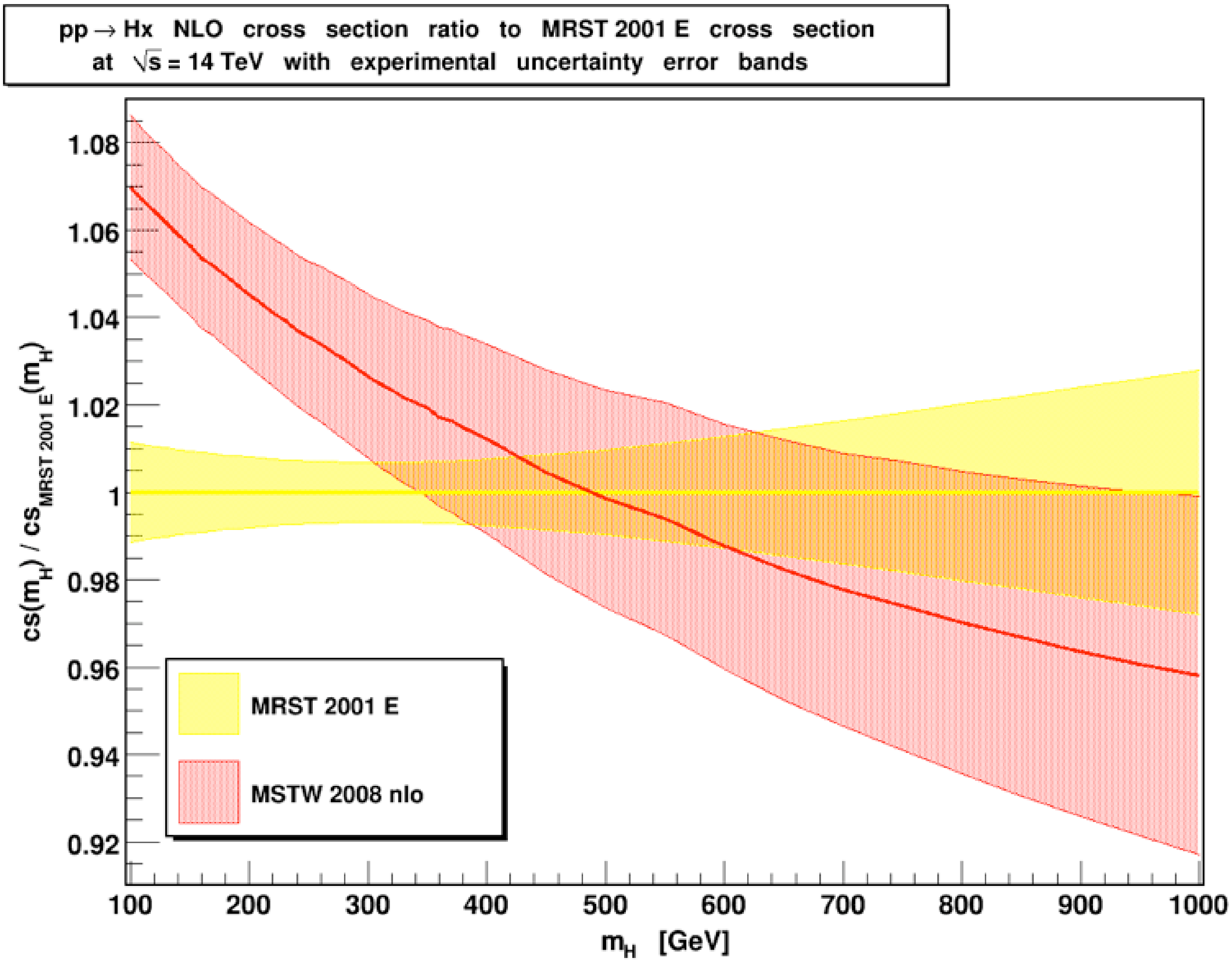






larger changes for small MH

MSTW cross sections



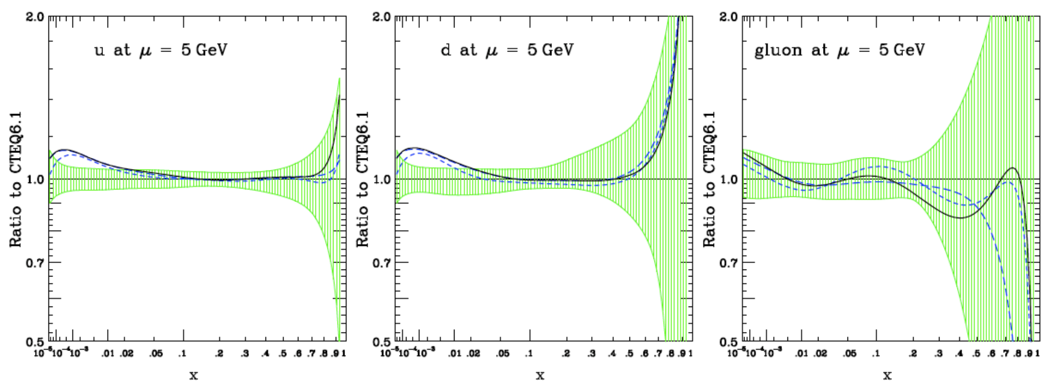
Comparison of *pdfs*: historical changes

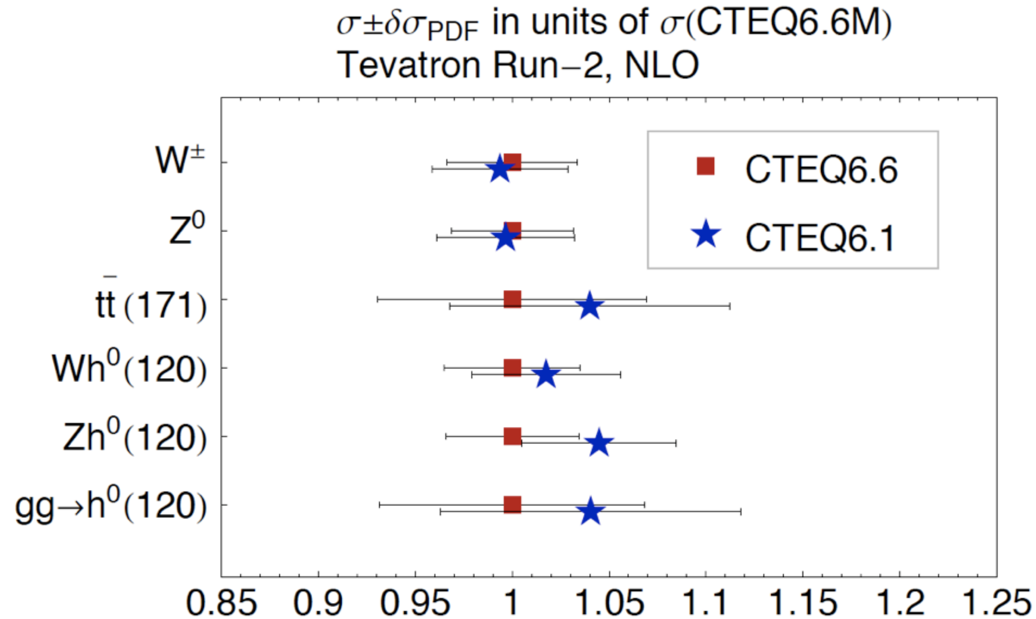
CTEQ

Heavy quark mass effect were absent in 6.1 and have been introduced in 6.5/6.6

New treatment of the strange quark density

Important changes for up, down and gluon





MSTW

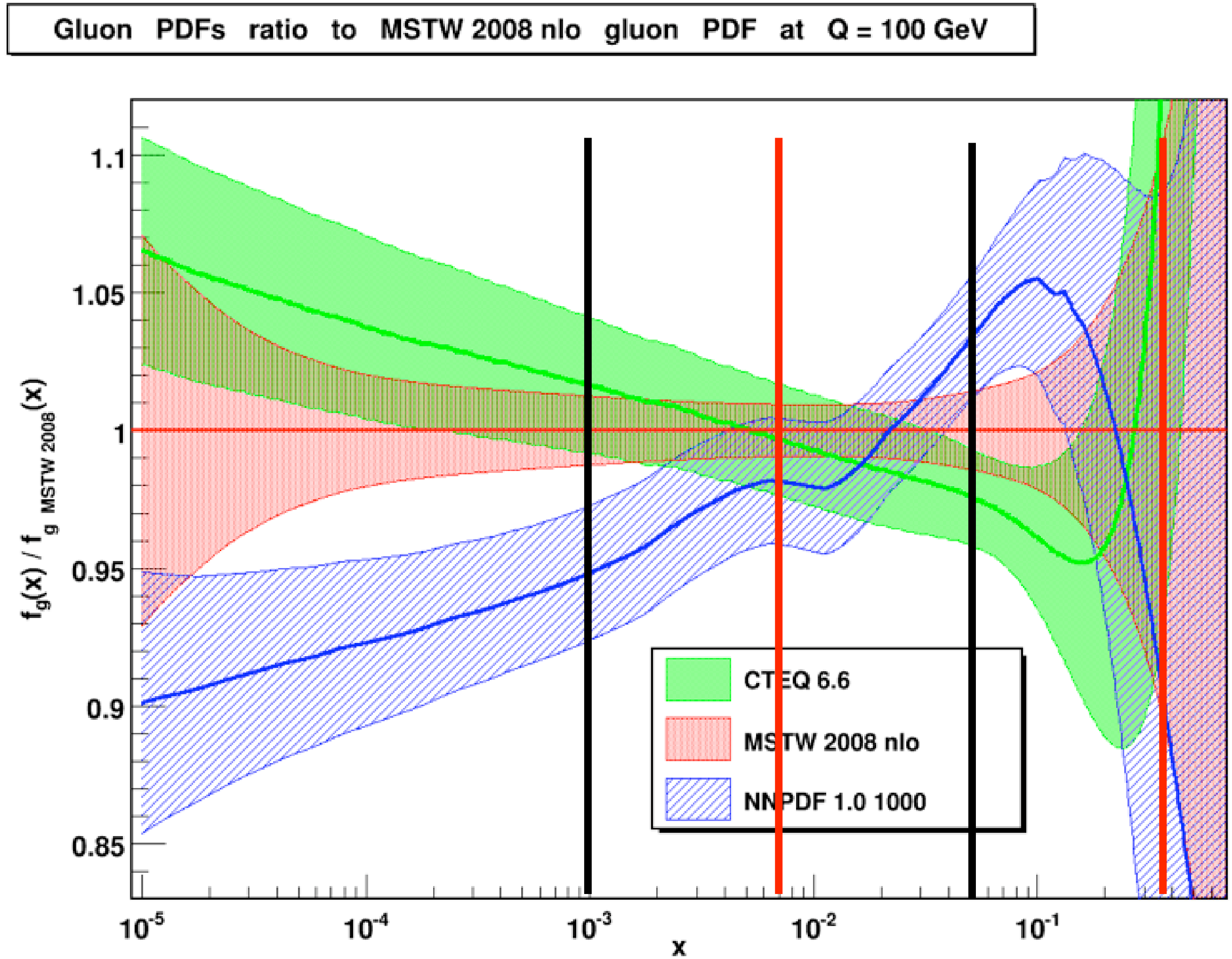
New data: neutrino str.fun., CCFR and NuTeV, Z rapidity, Run II inclusive jet prod., HERA

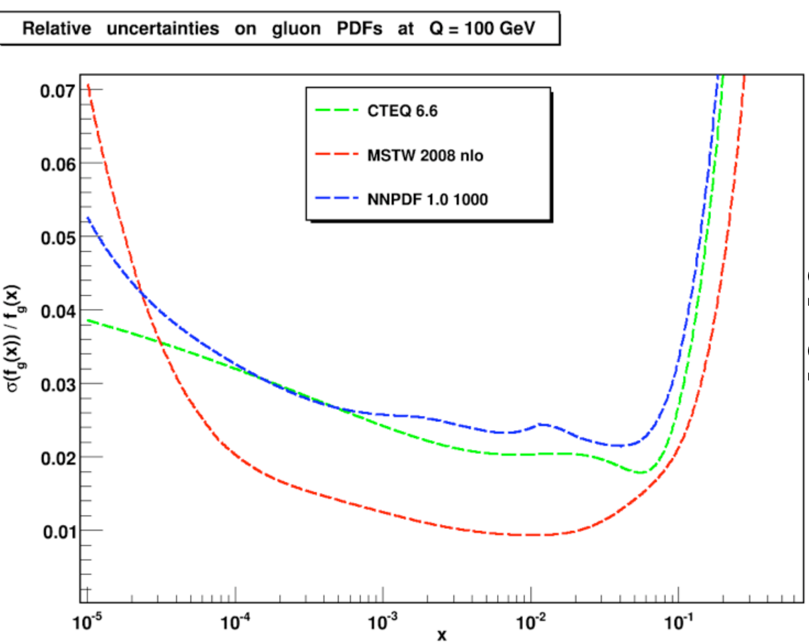
GM-VFNS to treat HQ effects (first introduced in 2006),

new richer parametrization

change in the alpha_s value (reduced from 2006 to 2008) yields larger gluon at small-*x*

Comparison of *pdfs*: latest released sets

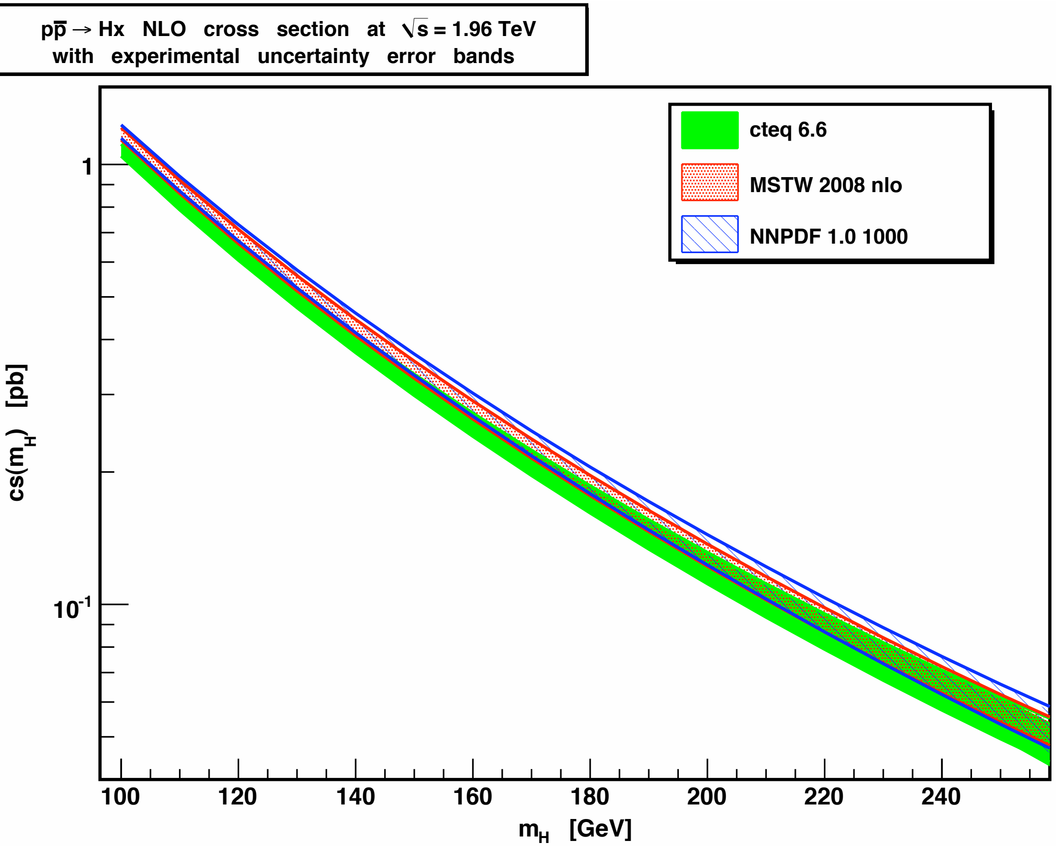




Size of uncertainties similar for CTEQ and NNPDF
Smaller by a factor 2 for MSTW

In the region constrained by HERA data
NNPDF agrees with CTEQ and MSTW

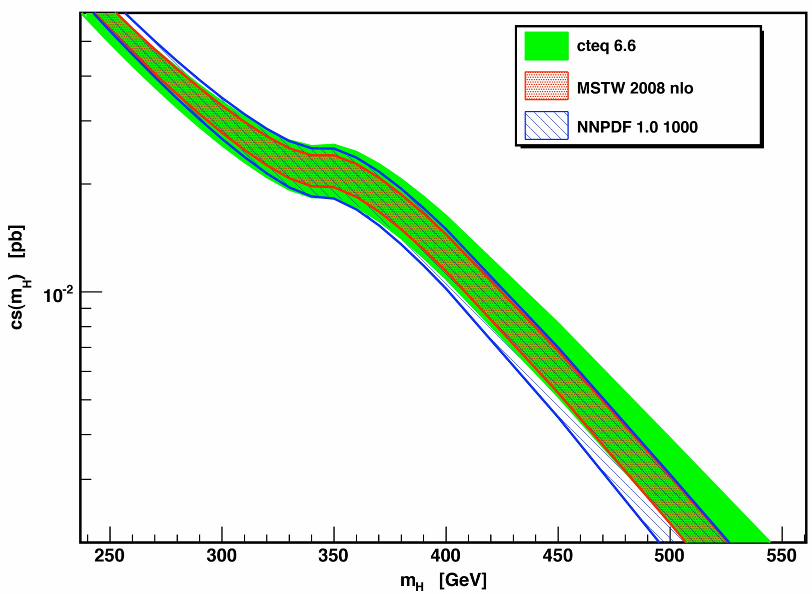
NLO xsecs: current *pdfs* uncertainties Tevatron

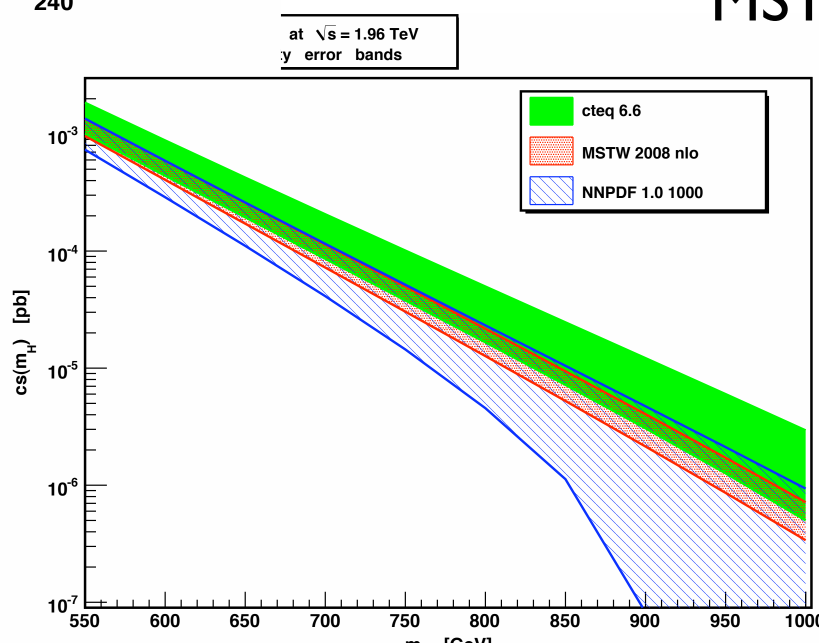


MSTW2008 and CTEQ6.6
do not overlap for MH<150 GeV

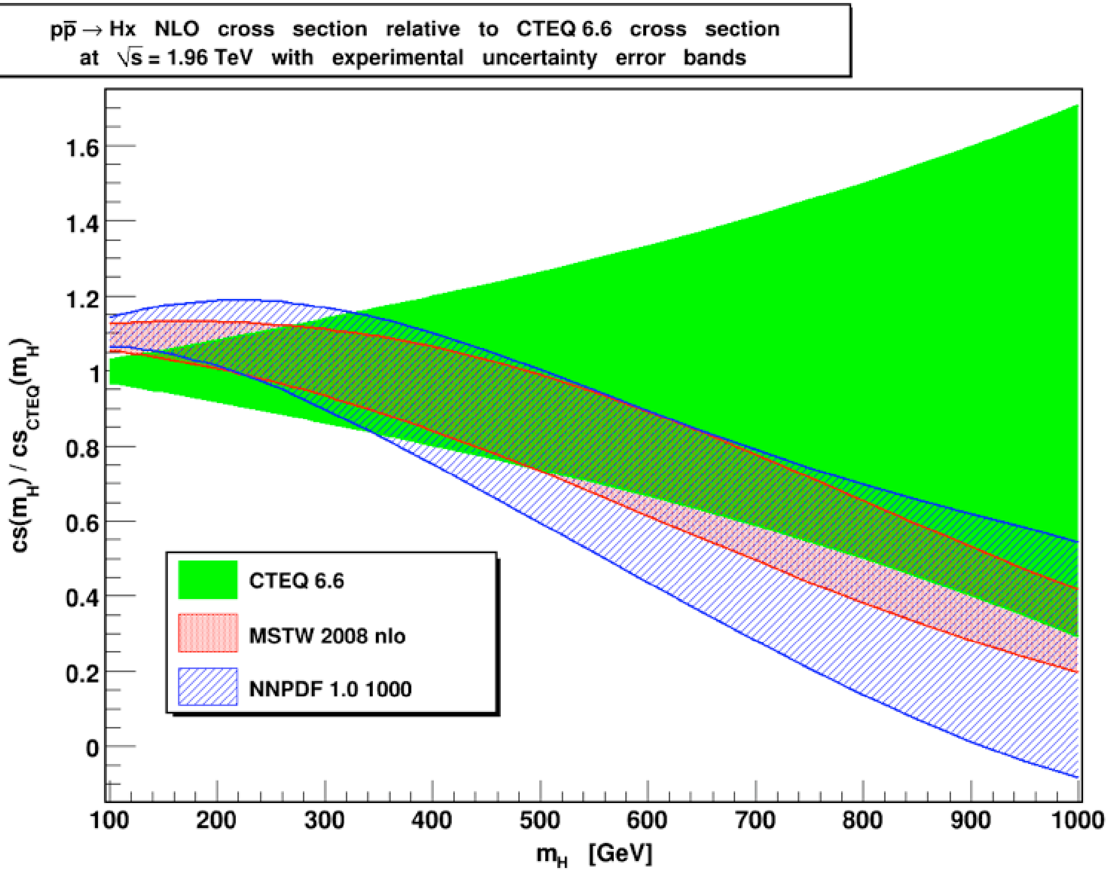
NNPDF1.0 agrees
with CTEQ6.6 for MH>200 GeV
with MSTW over entire eange

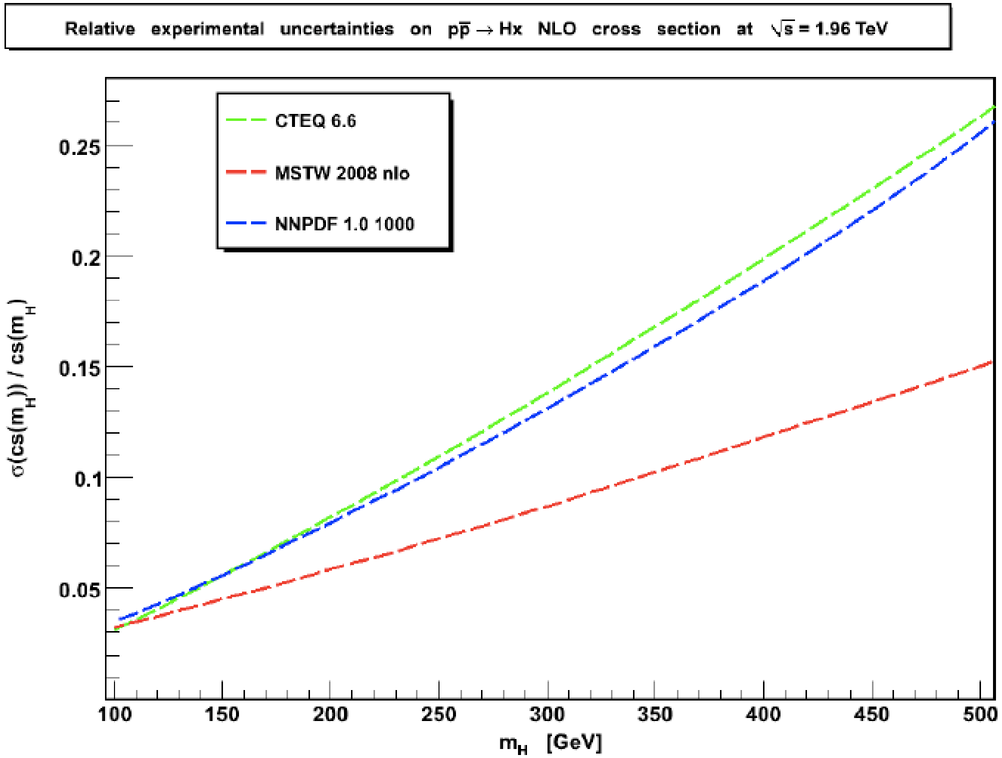
$$\alpha_s(m_Z) = \begin{array}{ll} \text{CTEQ6.6} & 0.118 \\ \text{NNPDF1.0} & 0.119 \\ \text{MSTW2008} & 0.120 \end{array}$$





Higgs total cross section at NLO-QCD: Tevatron

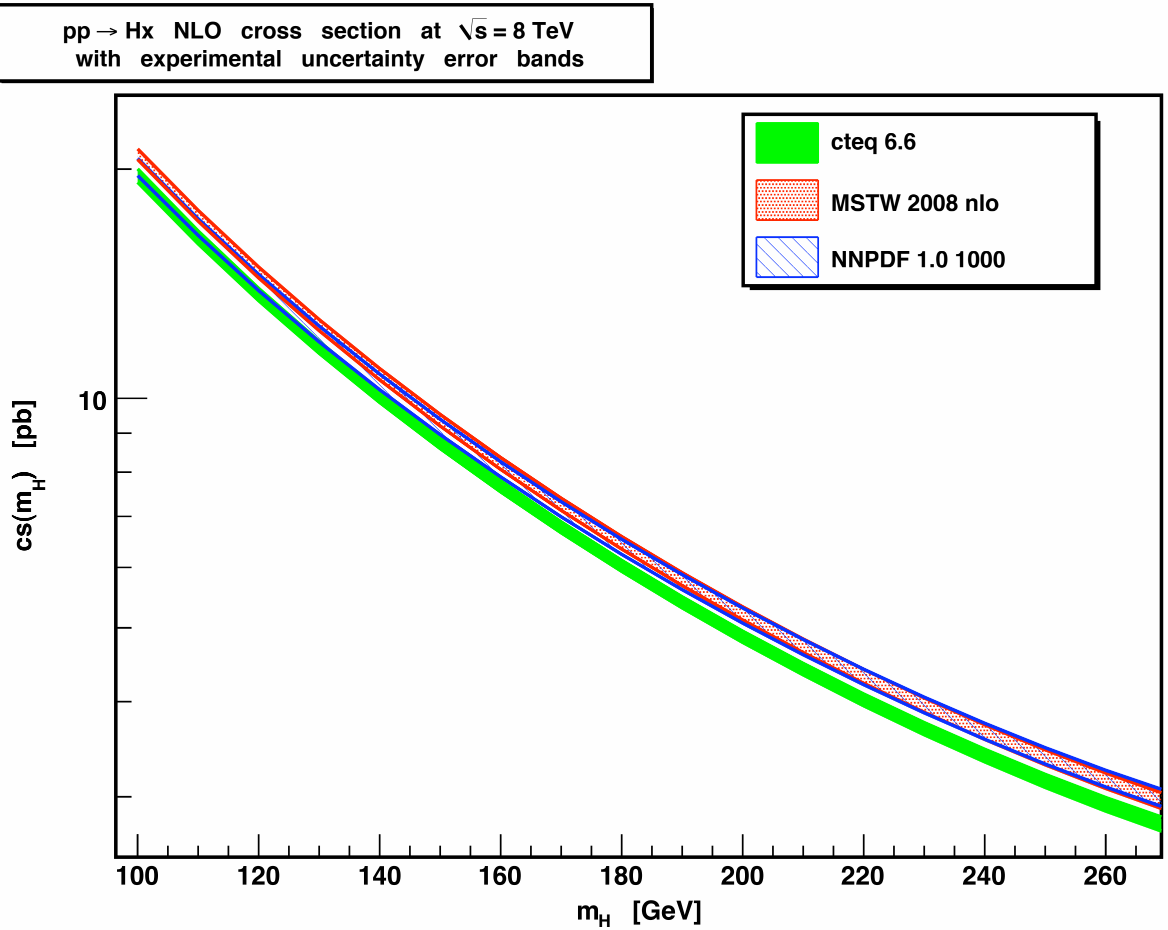




Similar uncertainties quoted by the 3 collaborations

For light MH, significant (up to 3σ) discrepancy (up to 9%) in the central values

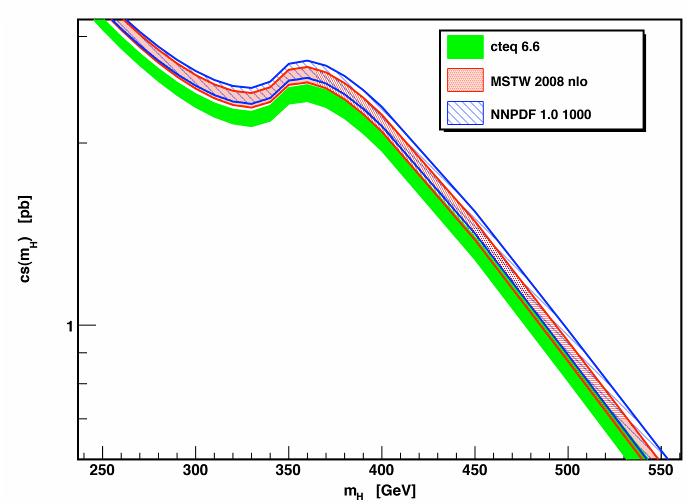
NLO xsecs: current *pdfs* uncertainties   LHC 8 TeV

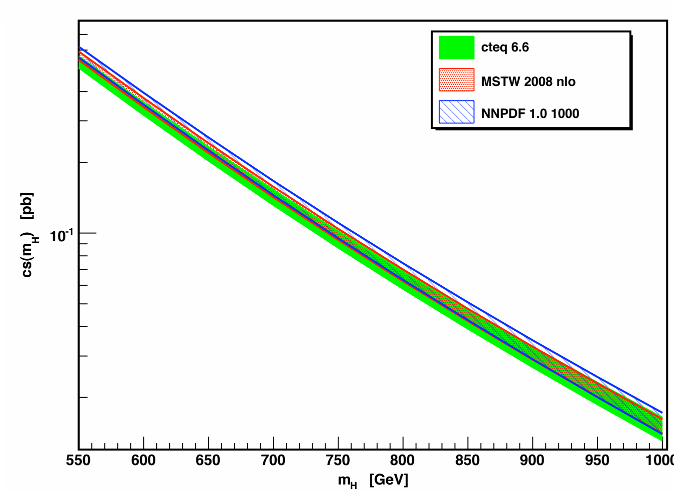


MSTW2008 and CTEQ6.6
do not overlap for MH<500 GeV

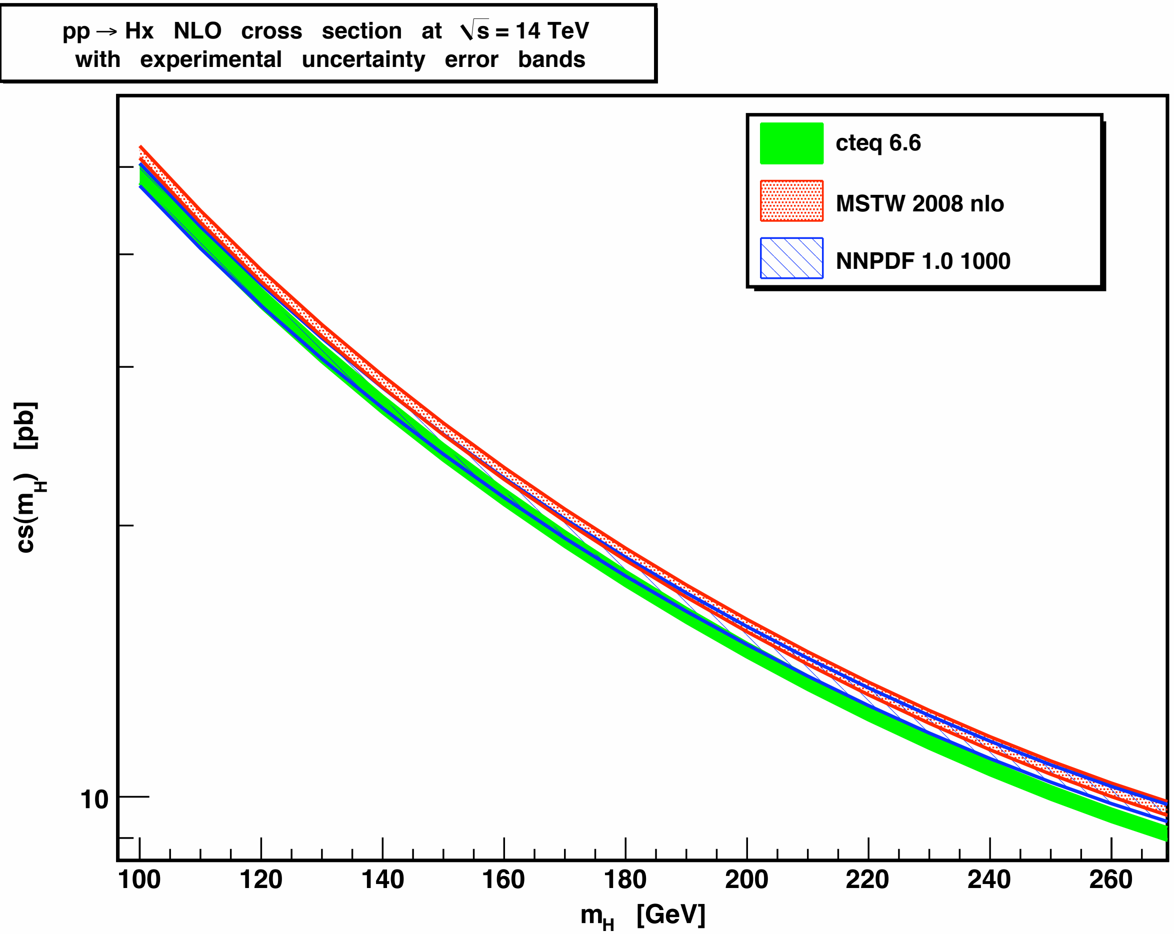
NNPDF1.0 overlaps
with CTEQ6.6 for MH<120 GeV
with MSTW for MH>200 GeV

$$\alpha_s(m_Z) = \begin{array}{ll} \text{CTEQ6.6} & 0.118 \\ \text{NNPDF1.0} & 0.119 \\ \text{MSTW2008} & 0.120 \end{array}$$





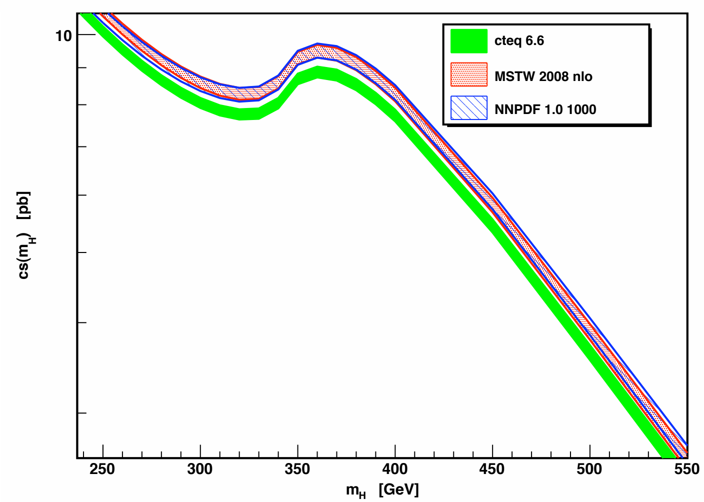
NLO xsecs: actual *pdfs* uncertainties LHC 14 TeV

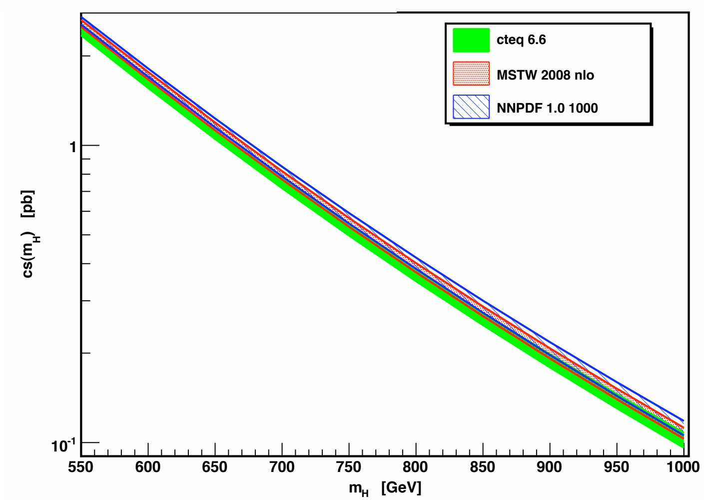


MSTW2008 and CTEQ6.6
do not overlap for MH<500 GeV

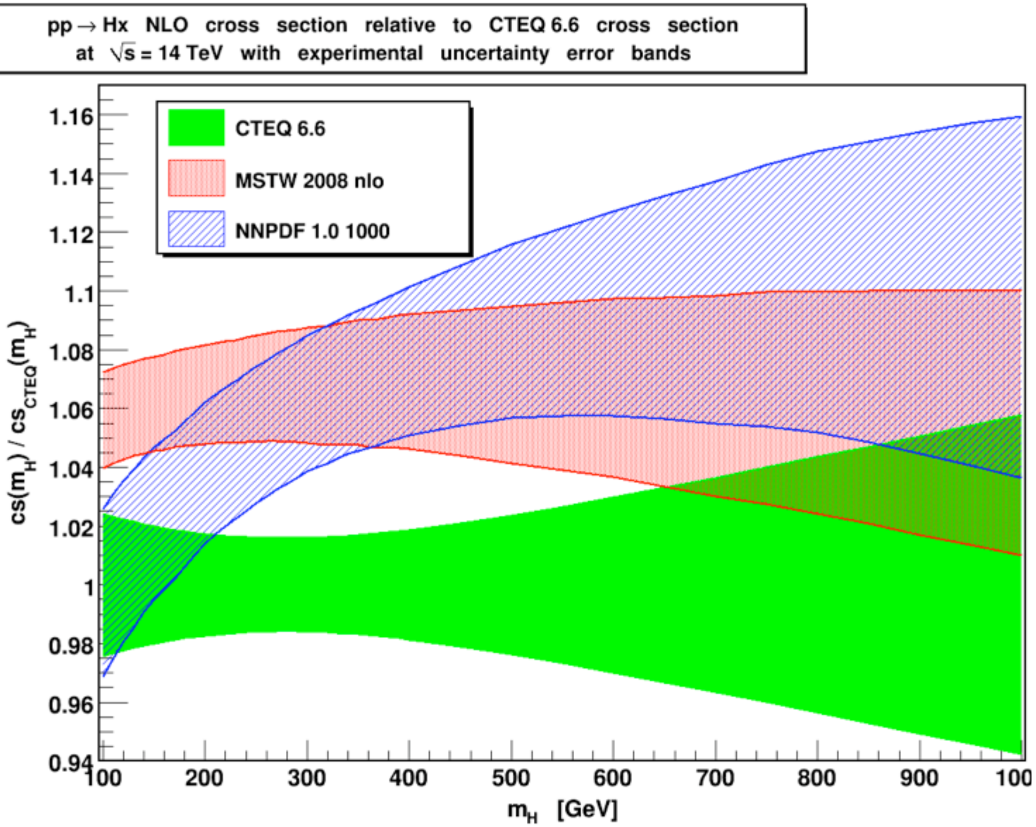
NNPDF1.0 agrees
with CTEQ6.6 for MH<180 GeV
with MSTW for MH>200 GeV

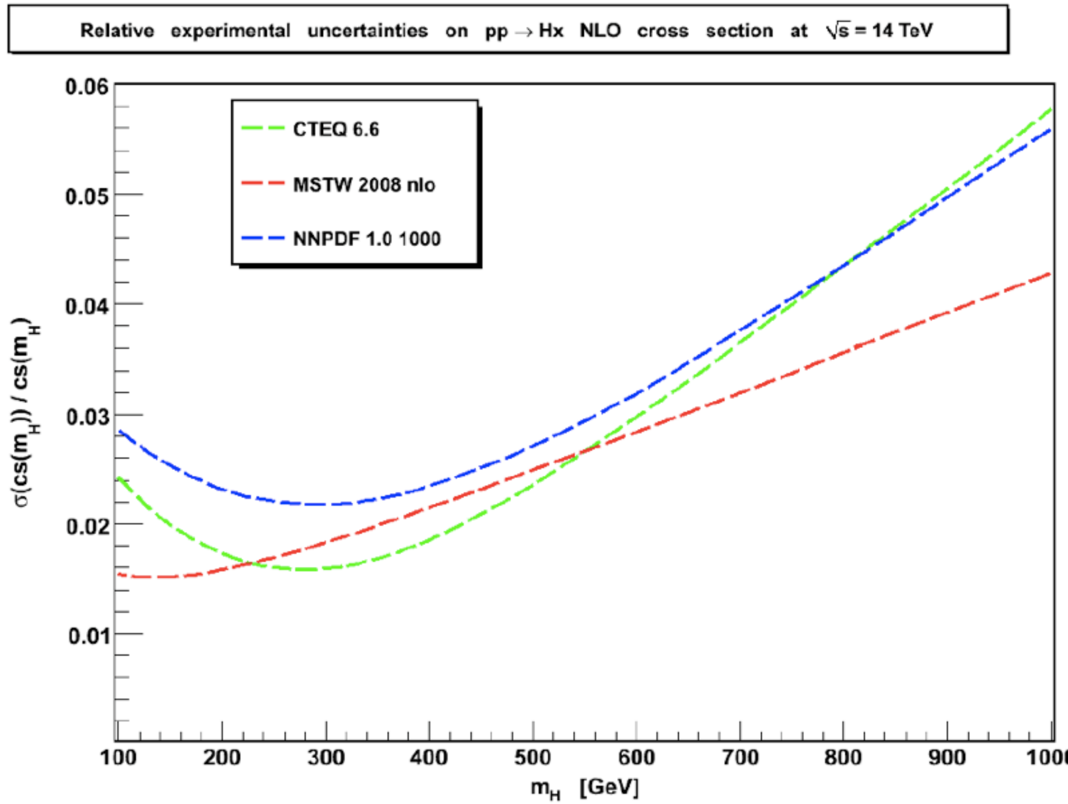
	CTEQ6.6	0.118
$\alpha_s(m_Z) =$	NNPDF1.0	0.119
	MSTW2008	0.120





Higgs total cross section at NLO-QCD: LHC 14 TeV





Similar uncertainties (worst agreement w.r.t. Tevatron)
quoted by the 3 collaborations

Significant (up to 3σ) discrepancy (6%) in the central values

The minimum of uncertainty for a range of Higgs masses corresponding to a range of *x* where HERA data play a major role on the gluon determination

Possible origin of the discrepancy

Differences in the gluon density can account for part of the discrepancy
but
the 3 collaborations use different values for alpha_s(mZ)
and the cross section has a strong dependence on this coupling

$$\sigma_{tot} = \alpha_s^2 \sigma_0 + \alpha_s^3 \sigma_1 + \dots \qquad \sigma_0 \sim \sigma_1$$

$$\alpha_s(m_Z) = 0.1176(20)$$

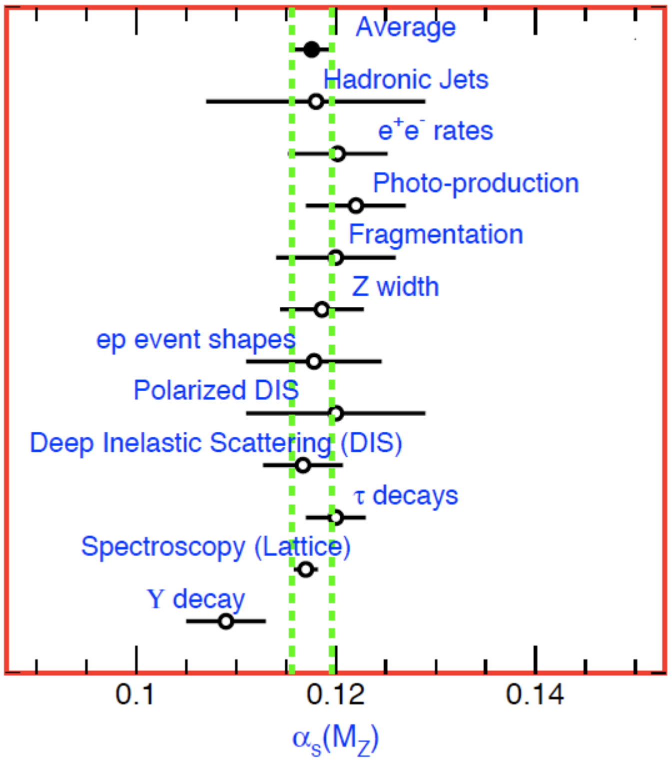
Naively, a change of alpha_s by 1σ implies a change of the cross section of 3-5 %

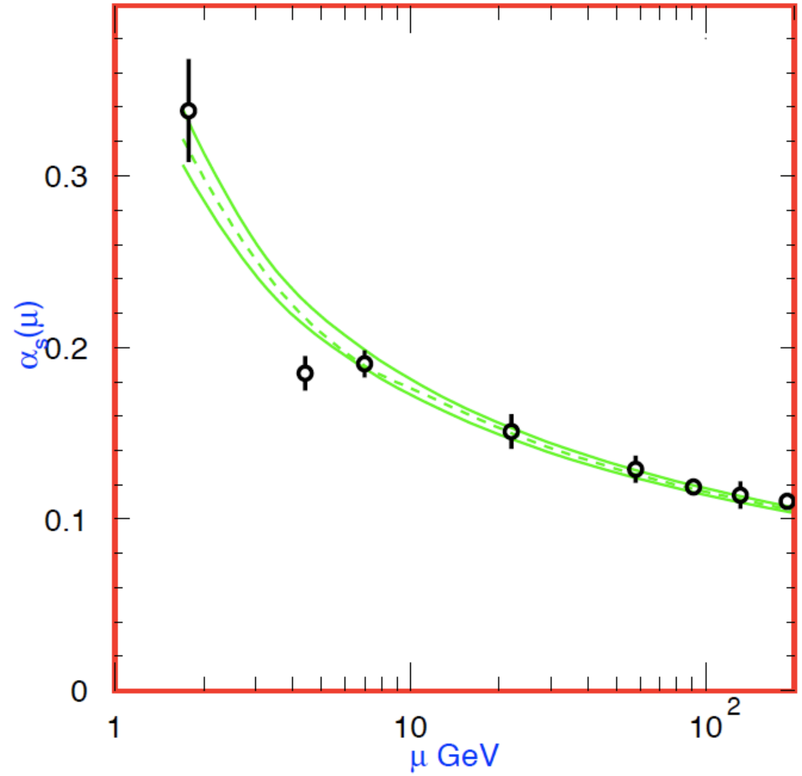
$\frac{2}{117} \sim 0.017$ for constant *pdf*s $0.034 < \delta\sigma_{tot} < 0.051$

but
parton densities and strong coupling should be consistent with each other

it is necessary to study the role of the uncertainties on alpha_s in the global fit of the *pdf*s

α_s





$$\alpha_s(m_Z) = 0.1176(20)$$

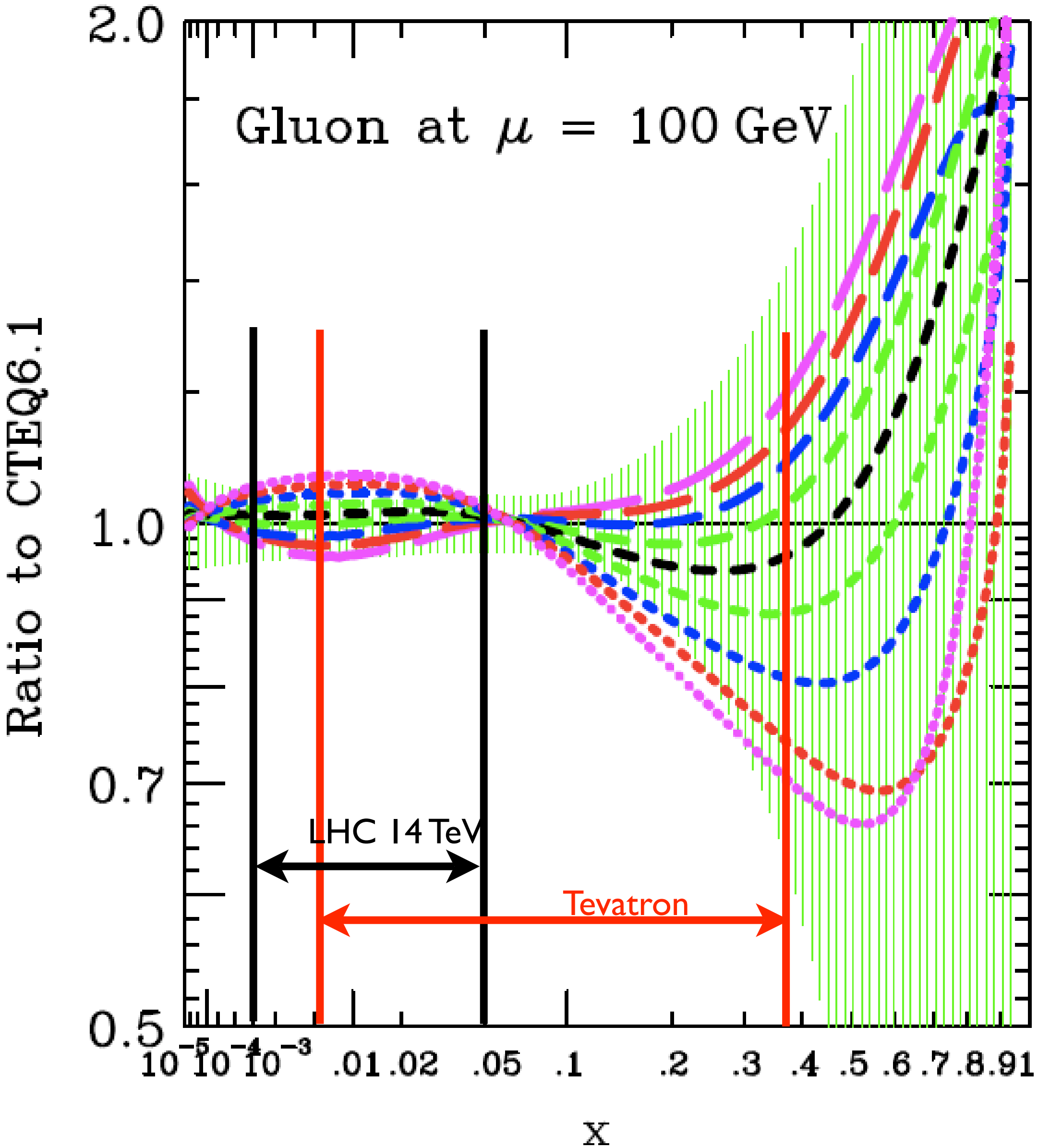
The strong coupling can be determined from observables that do not depend on the *pdfs* and then it can be used, with its error, to evaluate the impact of this parameter on the cross section

but

the strong coupling is very precisely measured in processes that involve the *pdfs*

it is necessary to evaluate to which extent alpha_s and the *pdfs* are correlated (e.g. gluon density is directly proportional to alpha_s)

α_s and gluon density in CTEQ6.6



gluon density obtained from a global fit with different values of alpha_s(MZ)

$$0.110 \leq \alpha_s(m_Z) \leq 0.126$$

compared with the uncertainty band of the best fit with central alpha_s

the vertical lines mark the x range to produce an object of 100 GeV with |y|<2

α_s dependence, MSTW

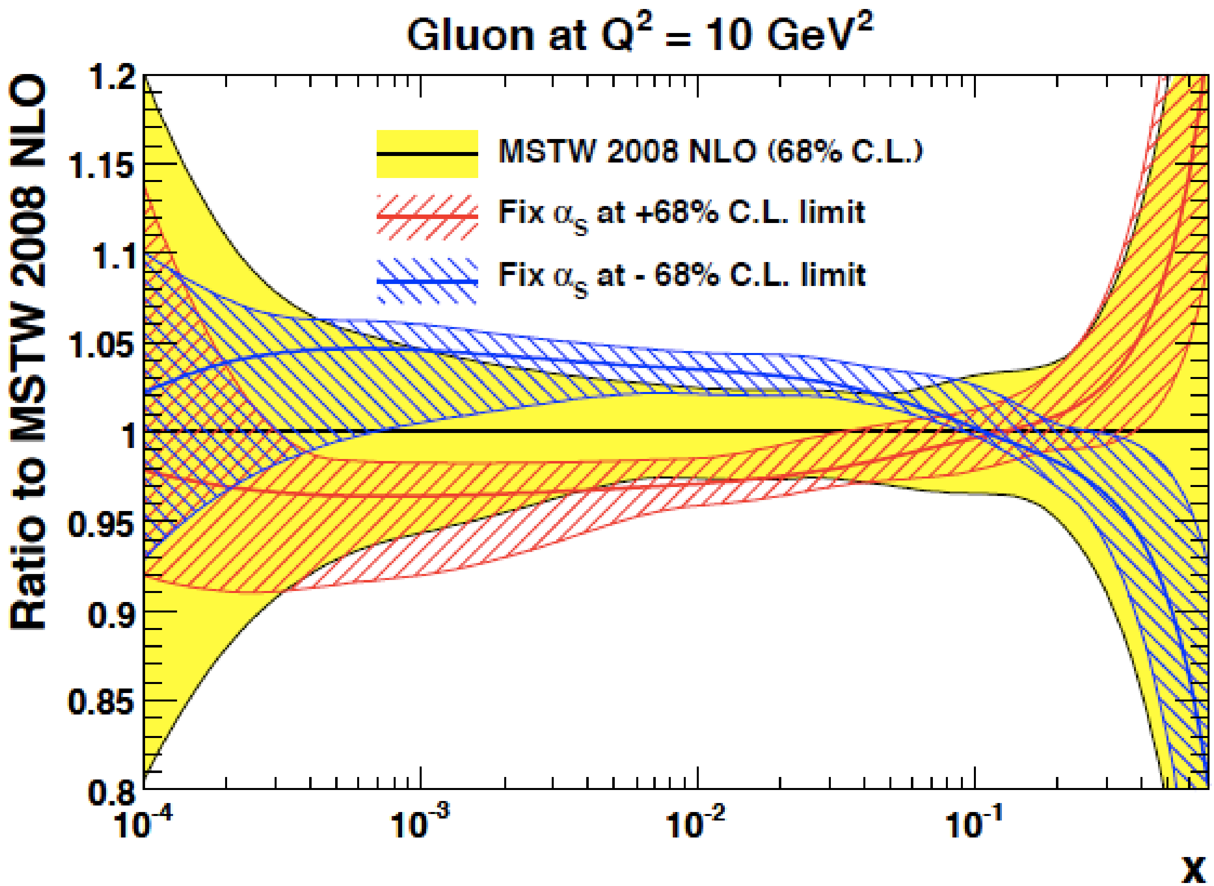
For MSTW, the uncertainty on the *pdf*s and on alpha_s are correlated

$$\alpha_s \in [\alpha_s^0 - 1\sigma,\ \alpha_s^0 + 1\sigma] \qquad \alpha_s^0 \equiv \alpha_s(m_Z) = 0.1202^{+0.0012}_{-0.0015}$$

For each of the 5 values:

$$\alpha_s^0 - 1\sigma, \quad \alpha_s^0 - 0.5\sigma, \quad \alpha_s^0, \quad \alpha_s^0 + 0.5\sigma, \quad \alpha_s^0 + 1\sigma$$

there are 40 pdf sets



Some *pdf*s spreads are much smaller that the central-value spread

α_s dependence, MSTW

For each of the 5 values compute the *pdf* spread (not necessarily symmetric)

$$(\Delta F^{\alpha_S}_{\rm PDF})_+ = \sqrt{\sum_{k=1}^{n} \left\{\max\left[\, F^{\alpha_S}(S_k^+) - F^{\alpha_S}(S_0),\ F^{\alpha_S}(S_k^-) - F^{\alpha_S}(S_0),\ 0\right]\right\}^2},$$

$$(\Delta F^{\alpha_S}_{\rm PDF})_- = \sqrt{\sum_{k=1}^{n} \left\{\max\left[\, F^{\alpha_S}(S_0) - F^{\alpha_S}(S_k^+),\ F^{\alpha_S}(S_0) - F^{\alpha_S}(S_k^-),\ 0\right]\right\}^2},$$

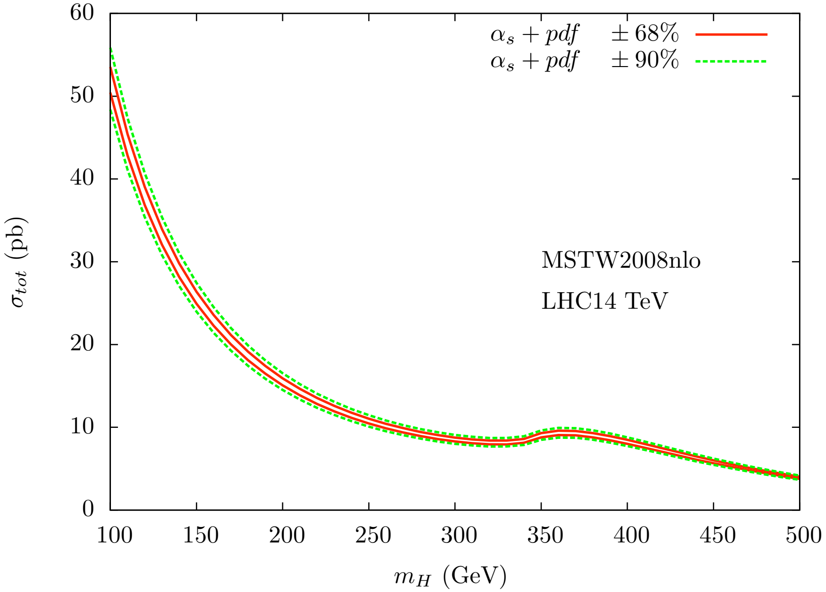
The (pdf+alpha_s) spread is obtained as follows

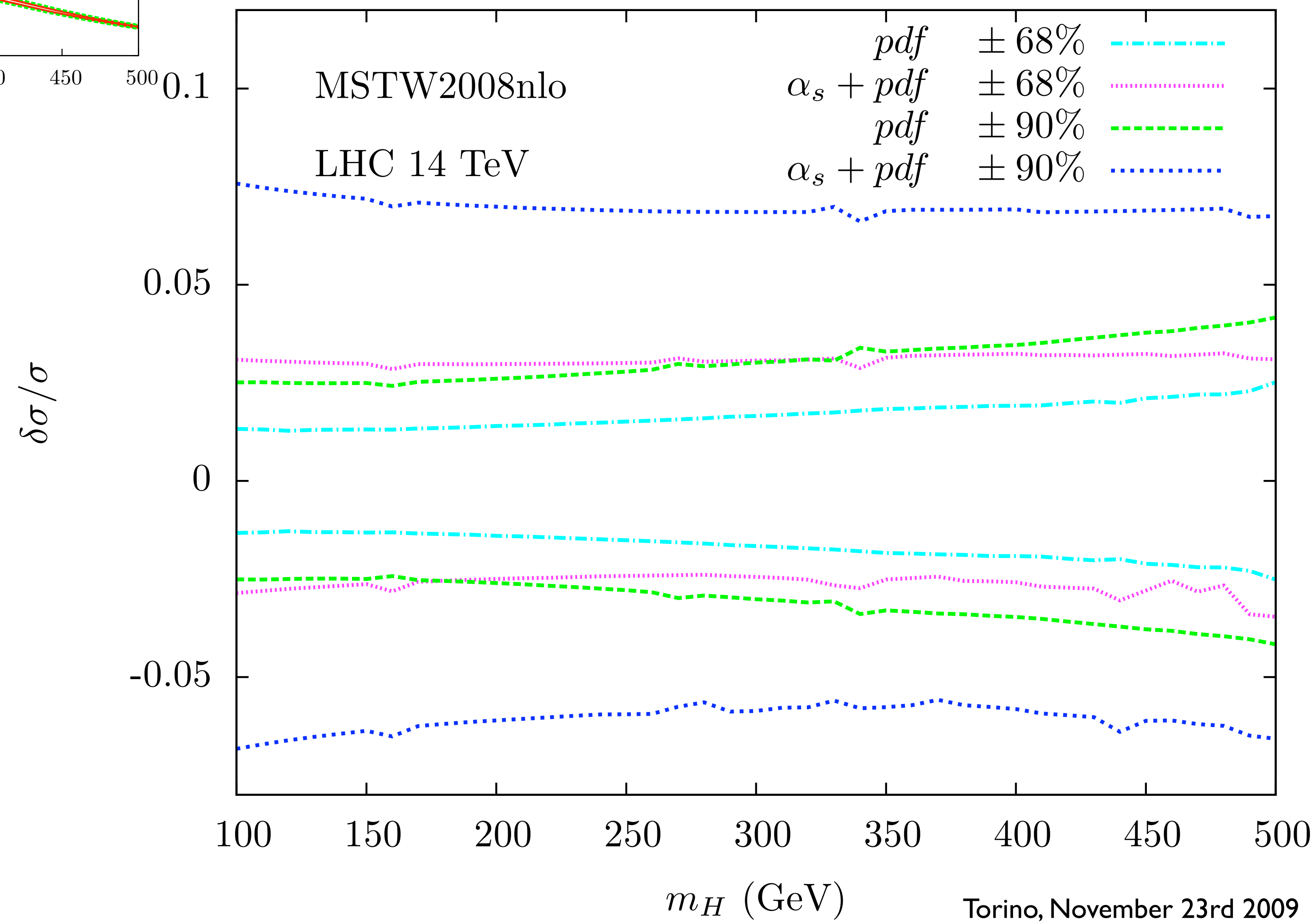
$$(\Delta F_{{\rm PDF}+\alpha_S})_+ = \max_{\alpha_S}\left(\{F^{\alpha_S}(S_0) + (\Delta F^{\alpha_S}_{\rm PDF})_+\}\right) - F^{\alpha_S^0}(S_0),$$

$$(\Delta F_{{\rm PDF}+\alpha_S})_- = F^{\alpha_S^0}(S_0) - \min_{\alpha_S}\left(\{F^{\alpha_S}(S_0) - (\Delta F^{\alpha_S}_{\rm PDF})_-\}\right),$$

Some *pdf*s spreads are much smaller that the central-value spread
This recipe is quite conservative

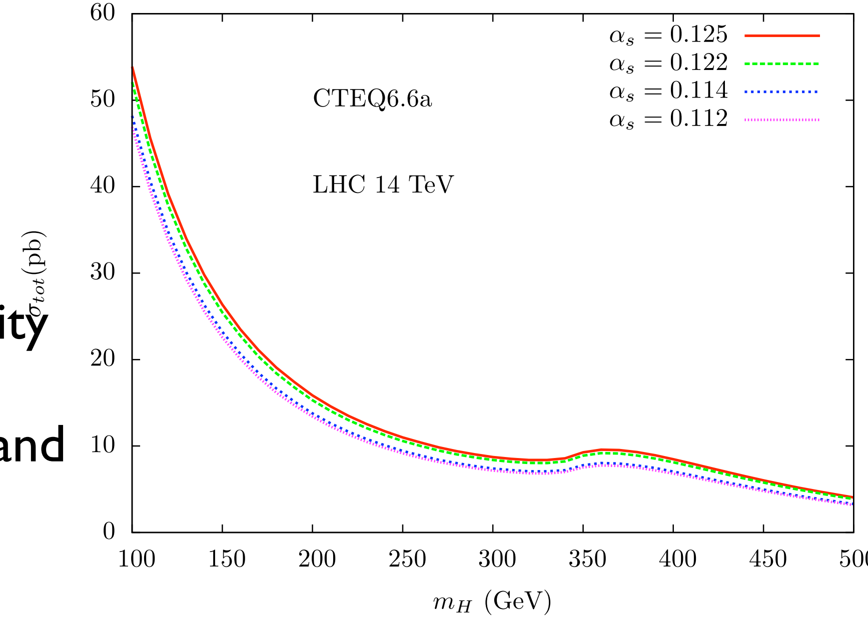
α_s dependence, MSTW





α_s dependence, CTEQ

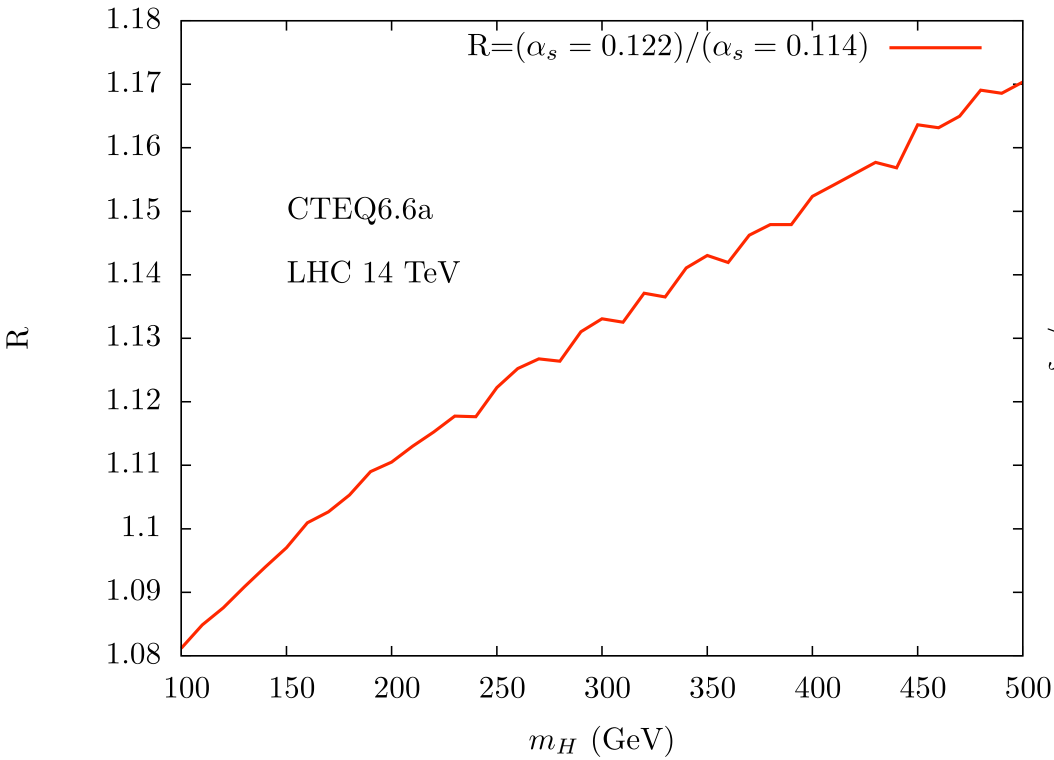
Series of global fits compatible with existing data using as reference value for alpha_s values within the uncertainty band of $\alpha_s(m_Z)$

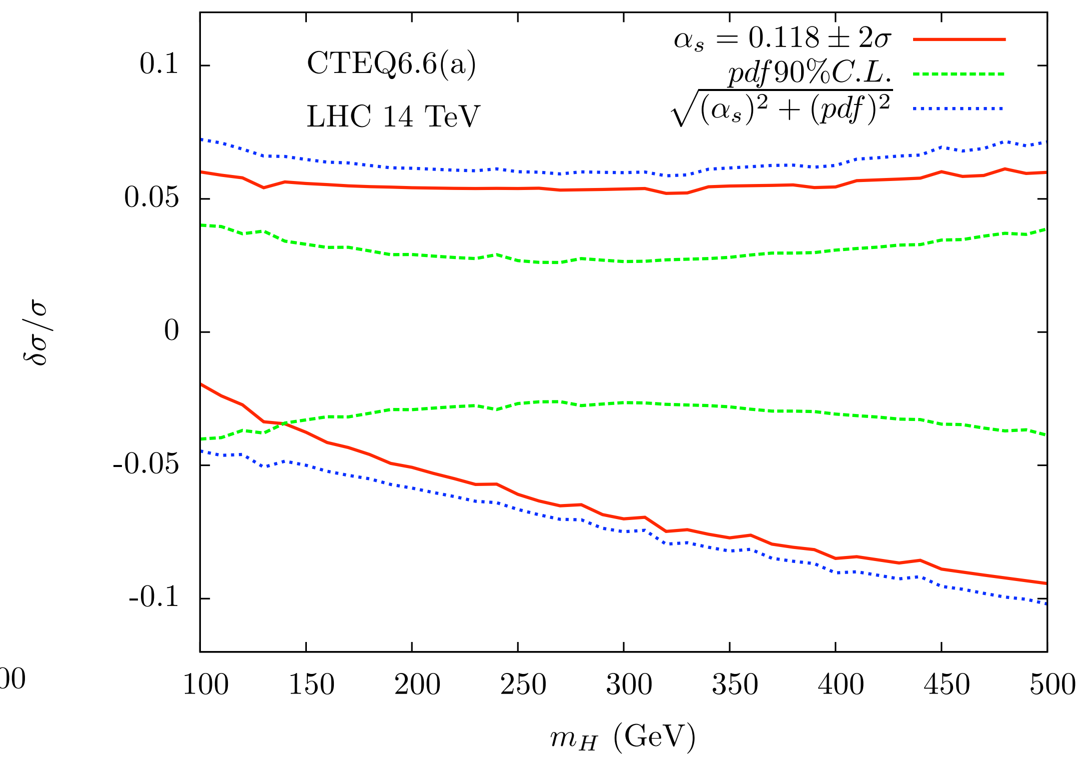


Every choice of $\alpha_s(m_Z)$ yields a different gluon density

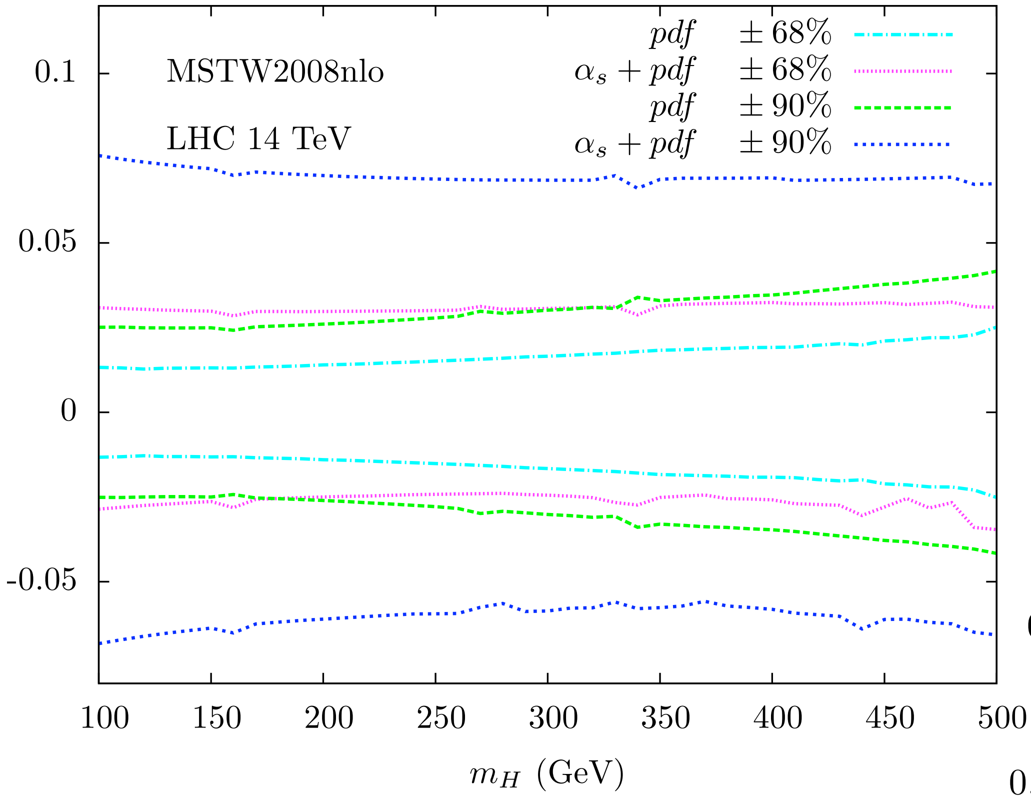
CTEQ assumes that the uncertainties due to the pdf and and those due to $\alpha_s(m_Z)$ are not correlated and can be combined in quadrature

The central values are instead strongly correlated





α_s dependence, comparison CTEQ6.6 vs MSTW2008

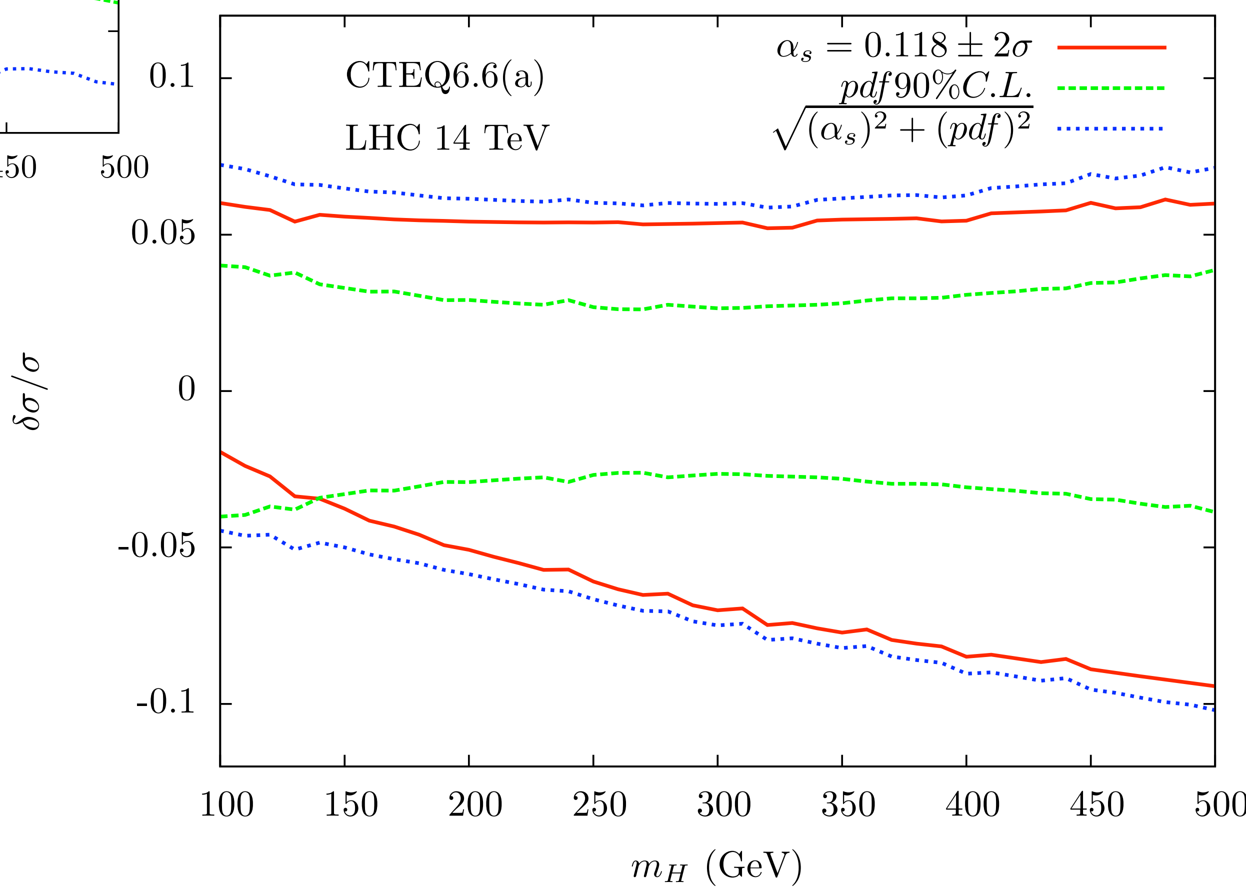


The assumptions are different

the overall size of the combined effect is similar

the estimate at small mH is different

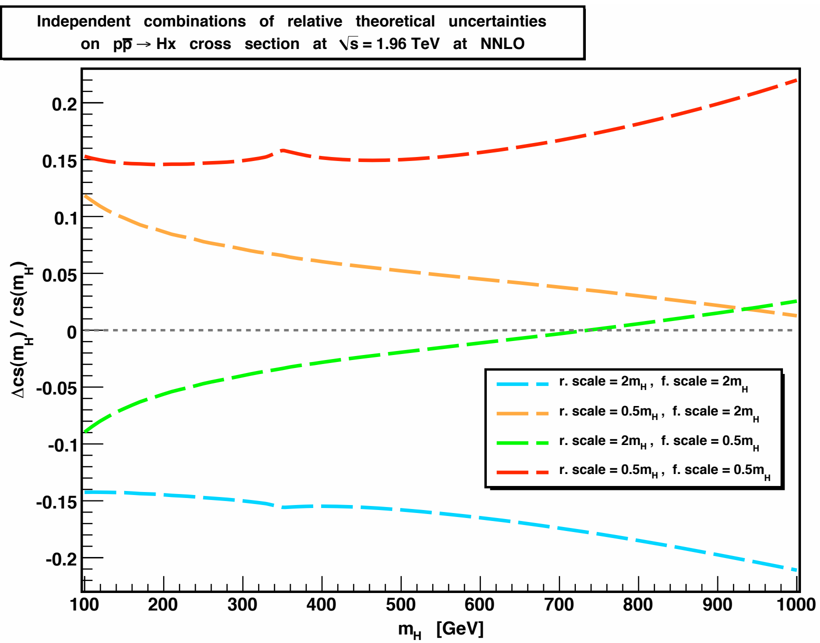
These larger uncertainty bands reduce the significance of the discrepancy of the two sets

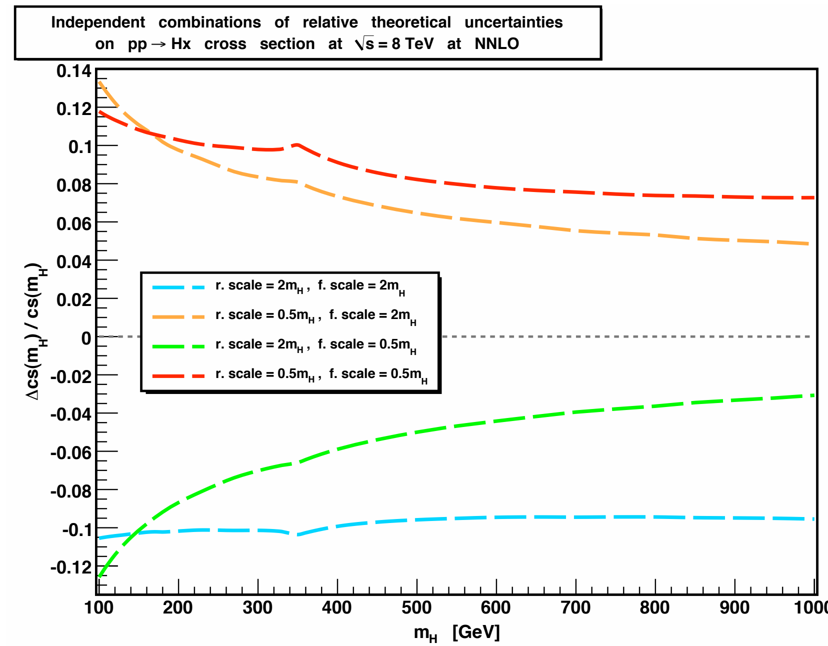


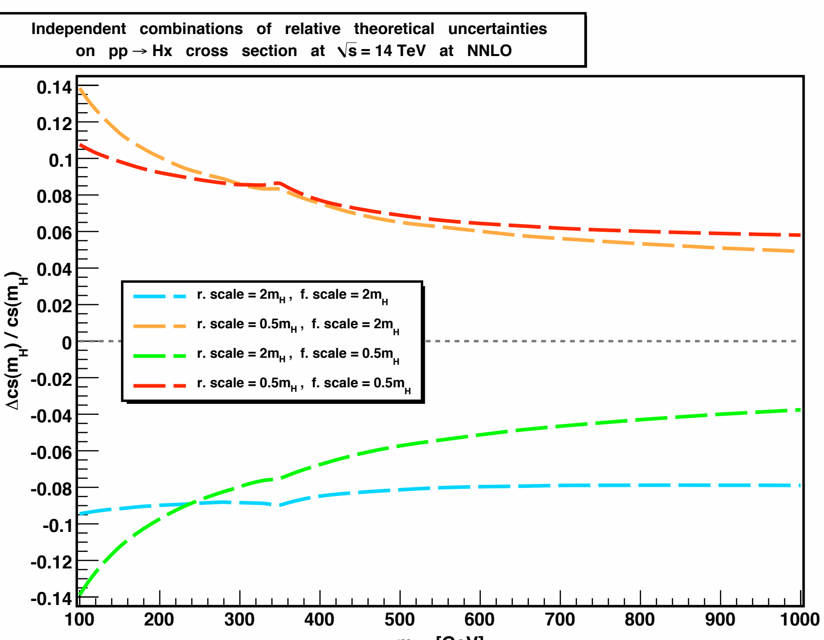
Scale dependence (NNLO-QCD):

Independent variation of factorization and renormalization scales.

NNLO-QCD contributions in the infinite top mass limit added to the exact NLO-QCD





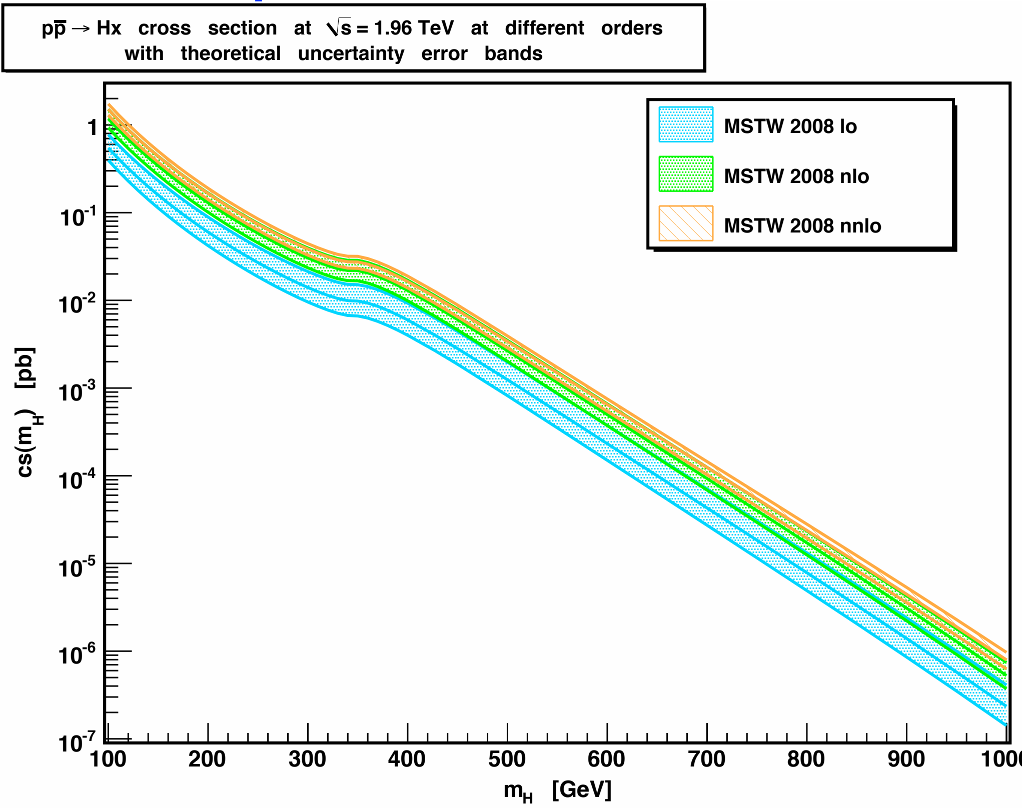


The lines show the 4 combinations in units MH:

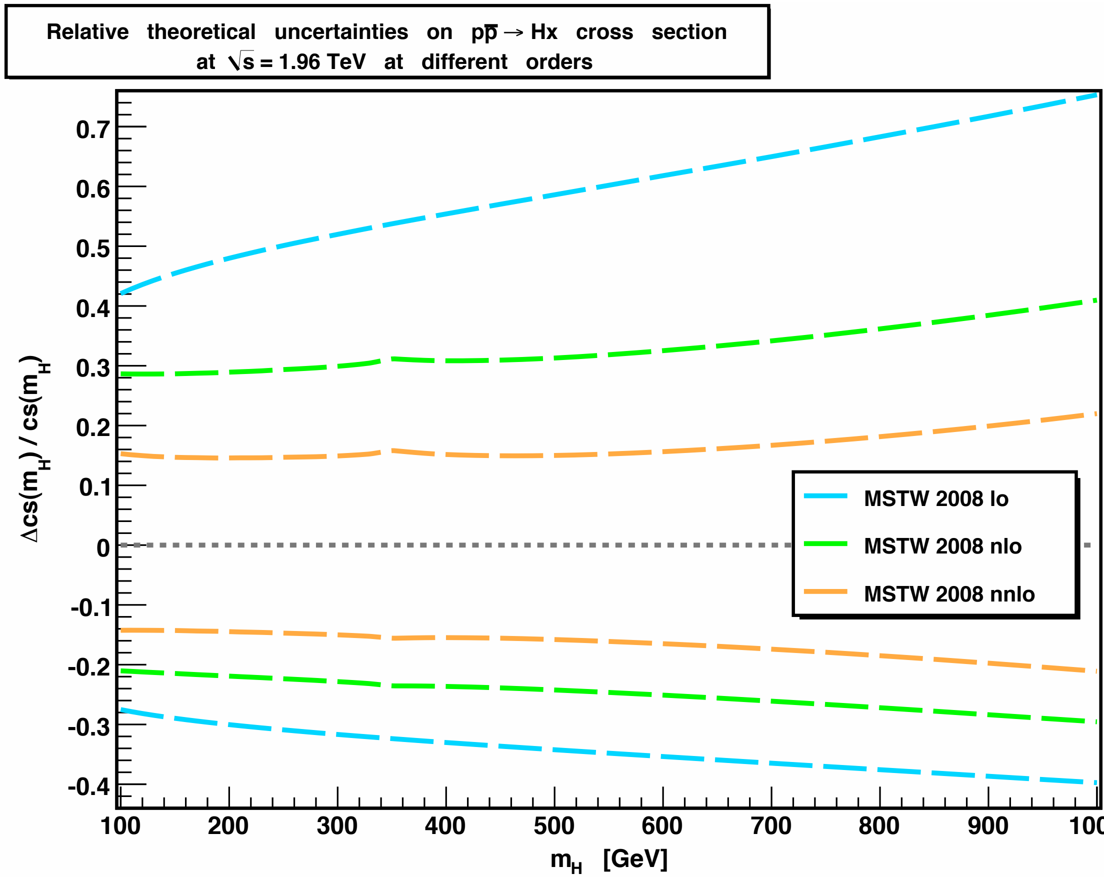
(μ_{ren}, μ_{fac}) =

(0.5, 0.5), (0.5, 2), (2, 0.5), (2,2)

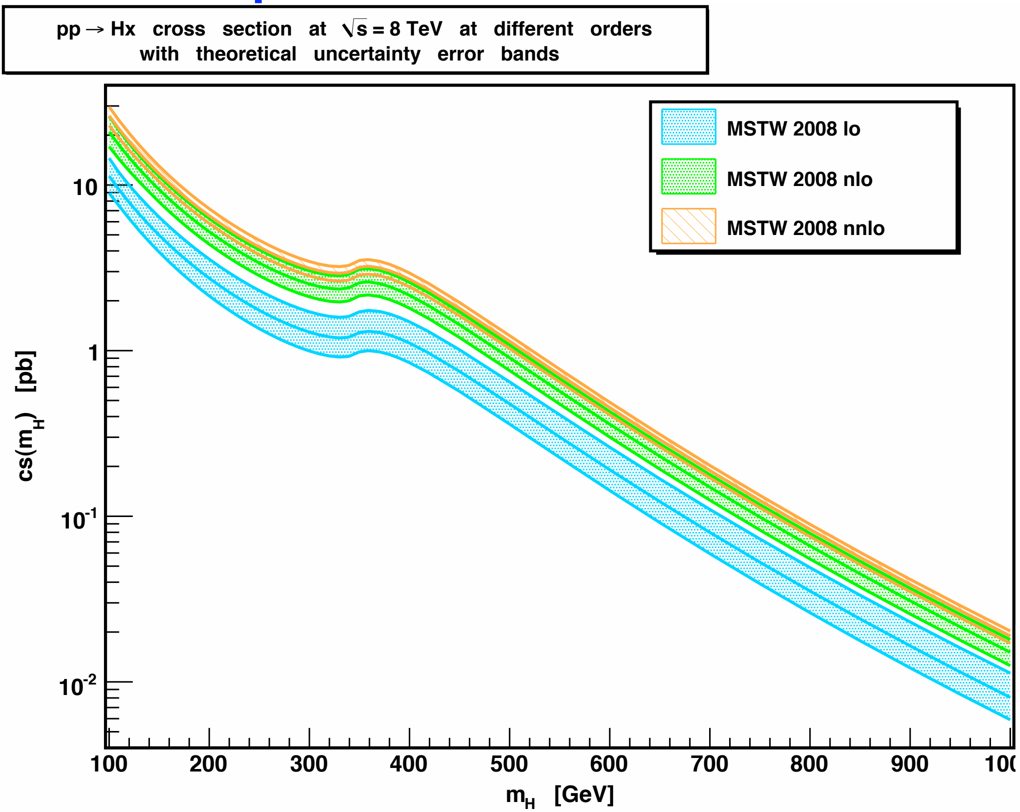
Scale dependence: Tevatron

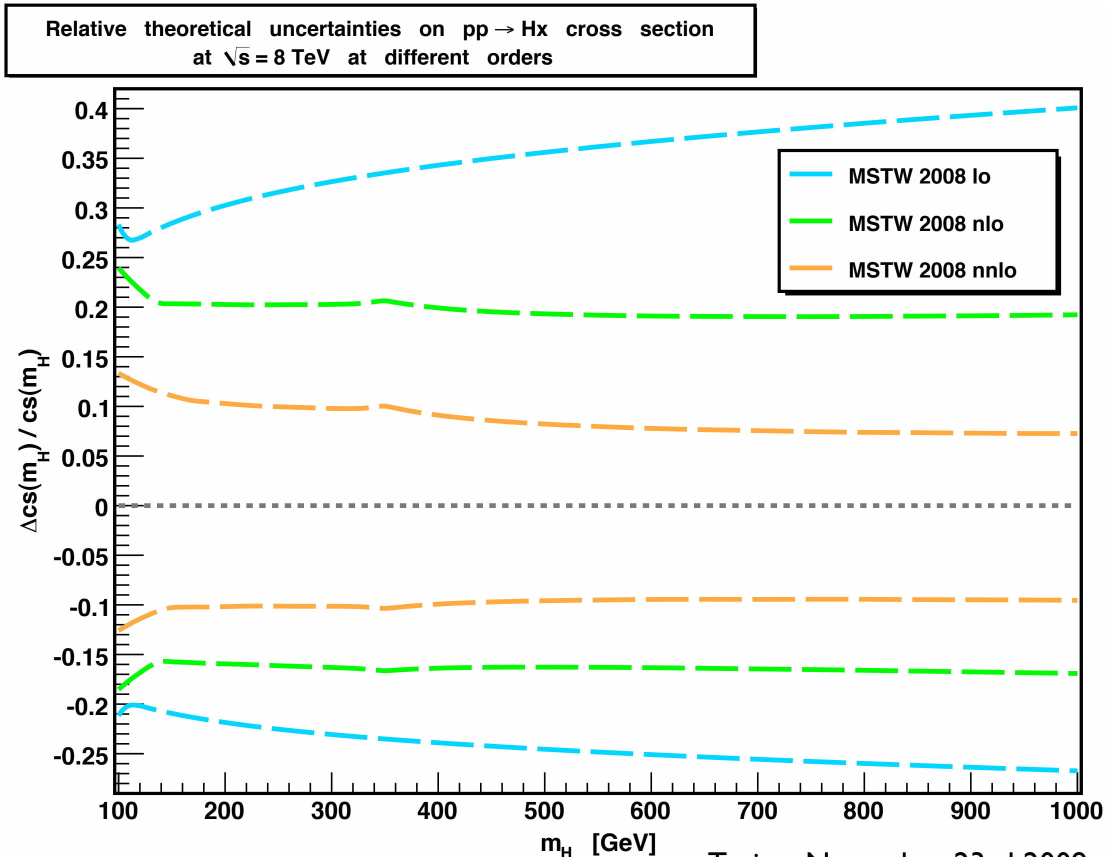


The bands are large
and have partial overlap

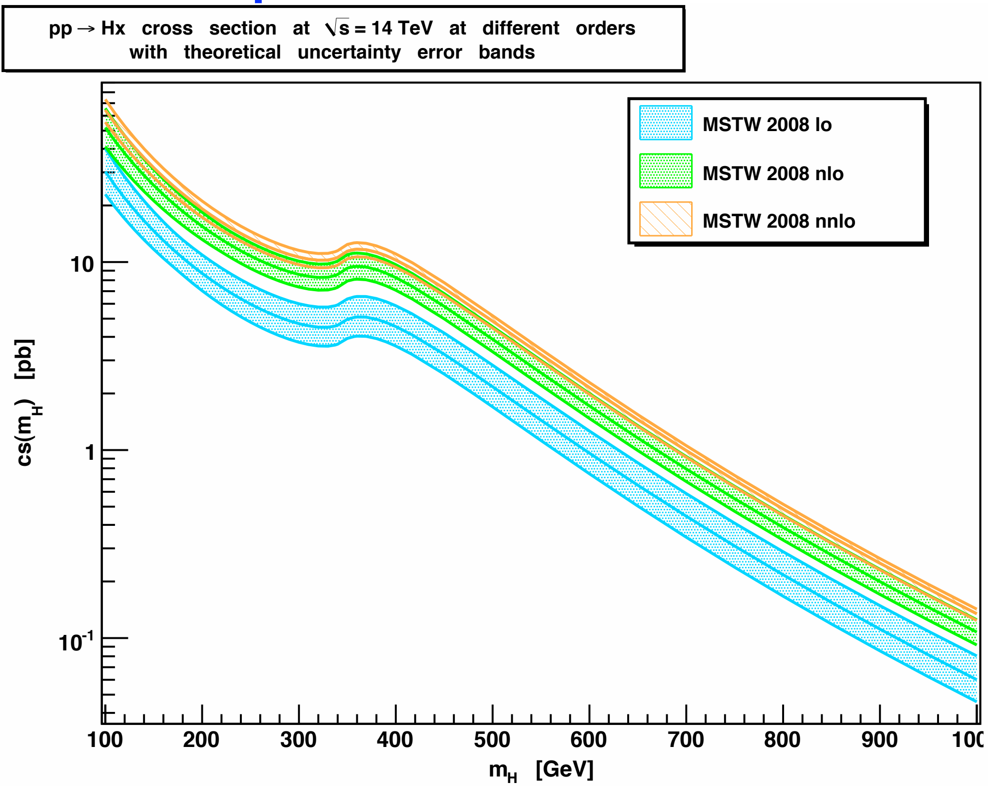


Scale dependence: LHC 8 TeV

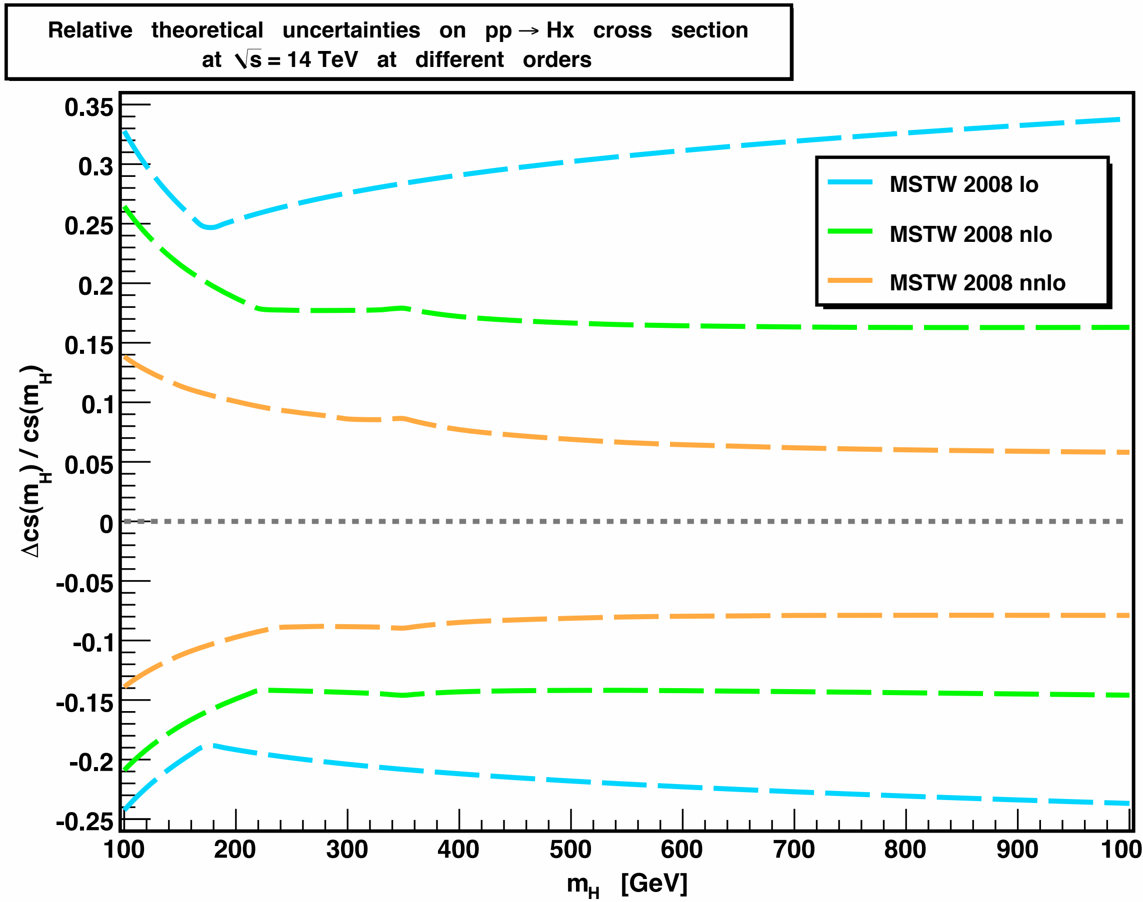




Scale dependence: LHC 14 TeV



The bands are thinner than
at the Tevatron
but have smaller overlap



Conclusions

- The experimental uncertainty on the *pdf*s affects the gluon fusion cross section at the few per cent level (the relevant *x* are well measured at HERA)
- Estimate of the size of the uncertainty similar for CTEQ, MSTW and NNPDF
- Not negligible differences of the central values between CTEQ6.6, MSTW2008 at NLO-QCD
- The role of alpha_s can partially reduce the significance of the discrepancy, enlarging the error bands
- Is the difference of the xsec, at NLO-QCD, part of the *pdf* uncertainty?

- The size of the uncertainty bands due to variation of the scales are at the level of 6-15% at NNLO-QCD;
  non trivial shape of the bands

- The accurate prediction of the gluon fusion total cross section requires, at least, the use of exact NLO-QCD predictions with all quark flavors