THE HIGGS AT THE TEVATRON: PREDICTIONS AND UNCERTAINTIES

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We update the theoretical predictions for the production cross sections of the Standard Model Higgs boson at the Tevatron in the gluon–gluon fusion and the Higgs–strahlung channels, including all relevant higher order QCD and electroweak corrections in perturbation theory. We estimate the different sources of uncertainties: the scale uncertainties, the uncertainties from the parton distribution functions and the related errors on the strong coupling constant as well as the uncertainties coming from the use of an effective theory approach in the $gg \to H$ process. We find that, when added in a consistent way, these errors amount to $\approx 40\%$ in the main $gg \to H \to WW^{(*)} \to \ell\nu\ell\nu$ search channel, implying that the recent exclusion of the Higgs mass range $M_H = 162$–166 GeV by CDF and D0 experiments should be reconsidered.

1 Introduction

The Standard Model (SM) of the electroweak and strong interactions crucially relies on the Higgs mechanism to generate the elementary particle masses[1,2]; the model predicts the existence of a scalar particle, the Higgs boson. This "Holly Grail" is currently searched at the Tevatron collider[3] which is sensitive to Higgs masses below $M_H \approx 200$ GeV, and its quest has started at the LHC where it could be discovered in the full theoretically allowed mass range, M_H up to $\approx$ 1 TeV, once the design energy and luminosity of the machine are attained.

In this talk, we will concentrate on the Higgs search at the Tevatron in the two main production channels: the gluon–gluon fusion process[4] $gg \to H$ with the subsequent decay[5] $H \to WW^{(*)} \to \ell\nu\ell\nu$, which is the most relevant decay channel[6] for $M_H \gtrsim 140$ GeV, and the Higgs–strahlung process[7] $q\bar{q} \to HV$ with $V = W/Z$, for a Higgs boson that mainly decays into $H \to b\bar{b}$, that is relevant in the low Higgs mass range[6], $M_H \lesssim 140$ GeV. Our purpose is to update the prediction for the production cross sections in these two channels together with a detailed study of the various sources of theoretical uncertainties affecting them. We will revisit the Tevatron Higgs mass exclusion band recently published[3]. An update of the gluon–gluon fusion mechanism was also recently performed[8,9], but it has not been the case for the $p\bar{p} \to HV$ process[10]. This talk is based on a recent paper[11] to which we refer for more details.

The gluon–gluon process is known at next-to-leading-order (NLO) in QCD both for infinite[12] and finite[13] loop quark masses. The calculation at next-to-next-to-leading-order (NNLO) has been done only in the infinite top mass limit[14] and the resumation effects were calculated[15] up to next-to-next-to-leading-logarithm (NNLL) approximation. The K–factors are very large, $K_{\rm NLO} \sim 2$ and $K_{\rm NNLO} \sim 3$, which could imply that higher order corrections might be large. The electroweak (EW) corrections are known exactly up to NLO[16] and there are mixed NNLO QCD-EW effects which have been calculated[9] in an effective approach valid for $M_H \ll M_W$.

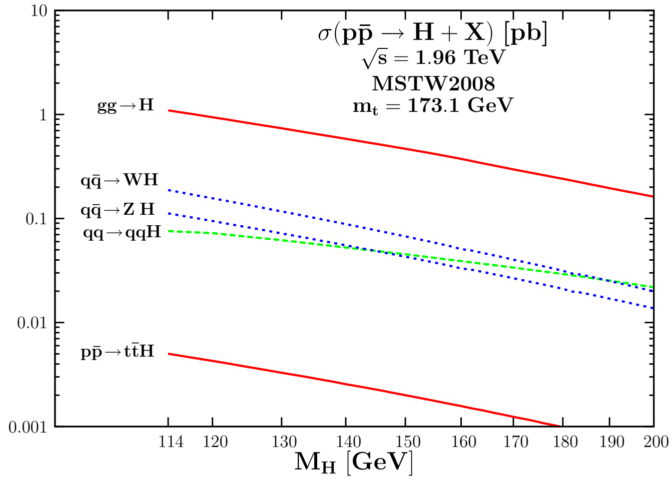

Figure 1: The total cross sections for Higgs production at the Tevatron as a function of the Higgs mass. The MSTW set of PDFs has been used and the higher order corrections are included as discussed in the text.

The starting point of our calculation is the Fortran code `HIGLU`[17] which evaluates the $gg \to H$ production cross section at exact NLO. We have implemented the NNLO QCD, the NLO EW and the mixed QCD-EW corrections within the code. We have restricted ourselves to the fixed order contributions and did not include the soft–gluon resumation, known to NNLL[15]. The reason, besides the fact that there is no parton distribution function (PDF) with gluon resumation included in (although the effects might be very small[18]), is that the QCD corrections to the cross sections including cuts, which should be the experimental input, is known only at NNLO[19]. There is also a $\simeq 25\%$ difference between the total cross section and the cross section with cuts, which should be seen in the NNLO scale variation[20]; see the discussion given in Ref. [10]. Finally, we have not studied background effects nor kinematical distributions[20].

The production cross sections, in which the relevant higher order effects are incorporated is shown at Tevatron energies in Fig. 1 for the updated value of the top mass and with the latest MSTW2008 public set of PDFs[21]. The renormalisation and factorization scales are fixed to the central values $\mu_F = \mu_R = M_H$ (see the next section).

The Higgs-strahlung process is known exactly up to NNLO in QCD[22,23] and up to NLO for the EW corrections[24]. The QCD K–factors are moderate, $K_{\rm NNLO} \sim 1.5$, and the EW corrections reduce the cross section by an amount of $\sim 5\%$. For the evaluation of the cross section, we have used the NLO code `V2HV`[17] in which we implemented the NNLO QCD and the EW corrections. The cross sections at the Tevatron for $p\bar{p} \to HV$ with $V = W, Z$ are shown in Fig. 1 for the latest MSTW2008 set of PDFs. Note that in the case of $p\bar{p} \to HW$, we did not include the effect of the CKM matrix elements and set the Cabibbo angle to zero[a]; including the actual values of V_{ud}, V_{us} would lead to a decrease of the cross section by $\approx -4\%$. On the other hand, including the HERA and Tevatron $W \to \ell\nu$ charge asymmetry data in the MSTW PDF set[25] would lead to an increase of the cross section by $\approx +3\%$ The combination of the two effects would then result into a decrease of the cross section of about 1% which is very small.

For completeness we also display the cross sections for the associated production process with top quarks $p\bar{p} \to Ht\bar{t}$ and the vector boson fusion mechanism $qq \to Hqq$ which do not play an important role at the Tevatron and are simply evaluated following Ref. [2].

[a] We thank R. Harlander for pointing this to us.

2 Theoretical uncertainties in the gluon–gluon fusion mechanism

a) Higher orders and scale variation

As the perturbative series is truncated, there is a dependence of the cross sections on the renormalisation scale μ_R which defines the strong coupling constant α_S and on the factorisation scale μ_F at which the matching between the perturbative matrix elements calculation and the non–perturbative parton distribution functions terms is done. The error due to the variation of these two scales is viewed as an estimate of the unknown higher-order terms and is the dominant source of error. Starting with the median scale $\mu_0 = M_H$ for which the central value of the cross section is obtained, the two scales μ_R, μ_F are varied within the interval, $\mu_0/\kappa \leq \mu_R, \mu_F \leq \kappa/\mu_0$, with a chosen value $\kappa = 2, 3, 4$, etc... For small higher order contributions as in the case of the Higgs–strahlung process, $\kappa = 2$ is in principle enough, but it may not be the case for $gg \to H$ where the K–factors are very large. In order to make a suitable choice of the κ value, we compare $\sigma^{\rm NLO}$ with the central $\sigma^{\rm NNLO}$ and we require the error band on the NLO results to catch the latter cross section. As seen on Fig. 2 (left) we need at least $\kappa = 3$ when using this criterion.

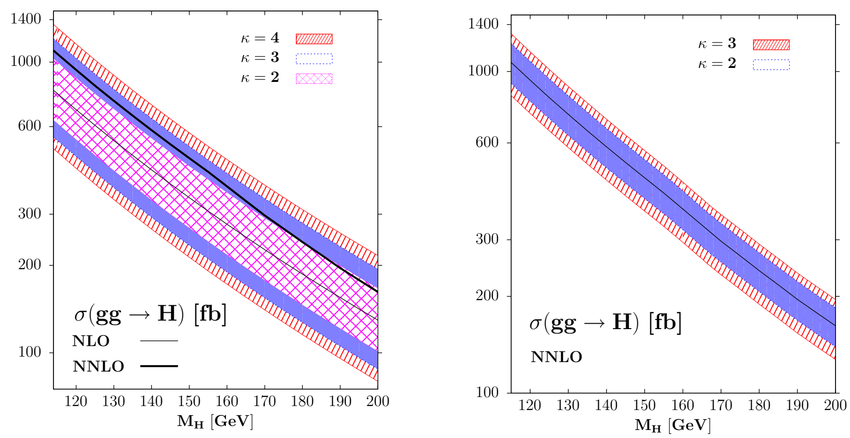

Figure 2: Left: the scale dependence of $\sigma^{\rm NLO}(gg \to H)$ at the Tevatron as a function of M_H for variations $M_H/\kappa \leq \mu_R, \mu_F \leq \kappa M_H$ with $\kappa = 2, 3.4$ compared to $\sigma^{\rm NNLO}$ evaluated at the central scale $\mu_R = \mu_F = M_H$. Right: the scale uncertainty bands of $\sigma^{\rm NNLO}$ for a variation in the domain $M_H/\kappa \leq \mu_R, \mu_F \leq \kappa M_H$ with $\kappa = 2, 3$.

Adopting this range for μ_R, μ_F for the NNLO cross section $\sigma^{\rm NNLL}$, we obtain a scale variation of $\Delta^{\rm scale}\sigma \simeq 20\%$ for the relevant range of M_H values. This has to be compared to the much smaller variation $\Delta^{\rm scale}\sigma \simeq 10\%$ adopted by the CDF/DO collaborations. Note that this $\sim 20\%$ amount is of the same order as the difference between the higher order effects in $\sigma^{\rm cuts}$ and $\sigma^{\rm total}$.

b) The PDFs and α_S uncertainties

The second most important source of errors in the $gg \to H$ mechanism comes from the PDFs uncertainties together with the experimental and theoretical errors on the strong coupling constant α_S. We estimate the PDF uncertainties with the help of the 2×20 PDF sets errors provided not only by the the MSTW collaboration[21], but also by the.CTEQ[26] or ABKM[27] collaborations. We take into accounts the spread of both uncertainties and the central values obtained within these different sets. The calculation gives a $\sim$ 5–10% error within all sets, but the ABKM central value is $\sim 25\%$ smaller than the CTEQ/MSTW central values; Fig. 3 (left).

In addition to the PDF uncertainties, one should also consider the errors coming from the uncertainties in the determination of the α_S value. Indeed we already have $\sigma^{\rm LO} = \mathcal{O}(\alpha_S^2)$ which implies that an error on the determination of the strong coupling constant may induce a non–negligible error on the final cross section. In the MSTW scheme, one has $\alpha_s(M_Z^2) = 0.1171 \, ^{+0.0014}_{-0.0014}$ (68%CL) or $^{+0.0034}_{-0.0034}$ (90%CL) at NNLO. We have computed the errors of the correlated PDF+$\Delta^{\rm exp}\alpha_S$ uncertainties using a new set–up[28] provided by the MSTW collaboration.

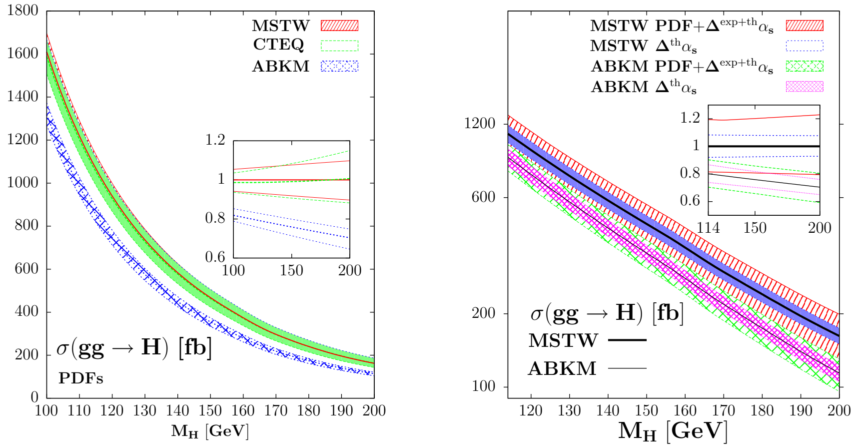

Figure 3: Left: the central values and the 90% CL PDF uncertainty bands in the NNLO cross section $\sigma(gg \to H + X)$ at the Tevatron when evaluated within the MSTW, CTEQ and ABKM schemes. In the insert, shown in percentage are the deviations within a given scheme and the CTEQ and ABKM central values when the cross sections are normalized to the MSTW central value. Right: the PDF+$\Delta^{\rm exp}\alpha_s$+$\Delta^{\rm th}\alpha_s$ uncertainties in the MSTW scheme using its new set–up and the PDF+$\Delta^{\rm exp}\alpha_s$+$\Delta^{\rm th}\alpha_s$ error in the ABKM scheme using a naive procedure[11]. In the inserts, shown are the same but with the cross sections normalized to the MSTW central cross section.

The result is shown in Fig.3 (right) and, as one can see, with only the experimental errors on α_S, one cannot reconcile yet the MSTW/CTEQ and ABKM predictions.

However, one also needs to consider the theoretical error on α_S that is due to the truncation of the perturbative series, the different heavy flavour schemes, etc... The MSTW collaboration estimates this error to be[21], $\Delta^{\rm th}\alpha_S = 0.003$ at NLO, which gives $\Delta^{\rm th}\alpha_S = 0.002$ at most at NNLO. Using again the central fixed–α_S MSTW PDF set and adding this last error, one obtains a total uncertainty of $\simeq 20\%$ which reconciles the MSTW/CTEQ and ABKM predictions.

The net result is that the total error due to PDF+$\Delta\alpha_S$ is much larger than the $\sim 5\%$ error that is obtained when using the PDF error only, as assumed by the CDF/D0 collaborations.

c) The use of an effective theory approach

The final set of uncertainties is specific to the gluon–gluon fusion mechanism which at NNLO is evaluated in an effective theory (EFT) approach where $M_Q \gg M_H$ for the contribution of a quark Q in the loop. It is very accurate for the top–quark loop[29], where studies of the effect of finite top mass have shown a difference below the percent level with respect to the EFT calculation for $M_H \lesssim 300$ GeV. Nevertheless this approach is not valid for the b–quark loop. and the omission of the b contribution leads to a $\simeq 10\%$ difference compared to the exact case.

In order to estimate the error of ignoring the b–loop contribution at NNLO, we rescale the difference calculated at NLO where the exact result is known by the relative NLO/NNLO K–factors, $\Delta^{\rm b-loop}_{\rm NNLO} = \frac{\sigma^{\rm NLO}_{\rm exact} - \sigma^{\rm NLO}_{\rm EFT}}{\sigma^{\rm NLO}_{\rm exact}} \times \frac{K_{\rm NLO}}{K_{\rm NNLO}}$. This gives a 1–2 % uncertainty. We then add a small uncertainty which is related to the difference between the on-shell bottom mass $M_b = 4.75$ GeV and the mass in the $\overline{\rm MS}$ scheme, $m_b(m_b) = 4.23$ GeV. It adds a $\sim$ 1–2 % uncertainty in the b–loop contribution, leading to a total error of a few % as shown in Fig. 4 (left).

Finally, in the electroweak corrections we have mixed QCD+EW corrections at NNLO[9]. They have been calculated in an EFT approach with $M_{W/Z} \gg M_H$, which is obviously not valid in practice. We thus should be cautious when using this (small) correction and assign an error which is of the same size. This error is comparable in size to the difference between the EW correction (calculated exactly at NLO) evaluated in the partial factorisation (PF) scheme compared to the result in the complete factorisation (CF) scheme, $\Delta_{\rm EW} = (\sigma^{\rm NLO-EW}_{\rm CF} - \sigma^{\rm NLO-EW}_{\rm PF})/\sigma^{\rm NLO-EW}_{\rm CF}$. This gives an error of 3.5% at most as shown in Fig. 4 (right).

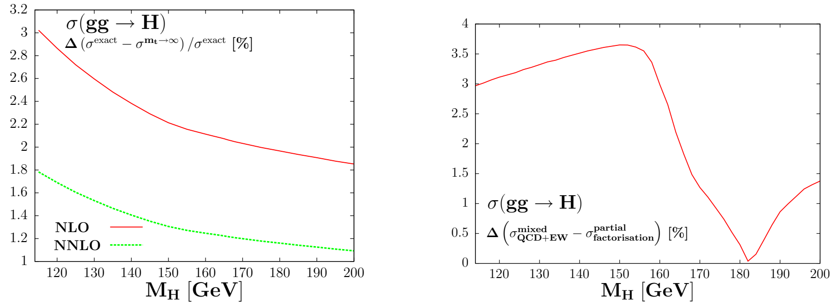

Figure 4: Left: relative difference (in %) at Tevatron energies and as a function of M_H between the exact NLO and NNLO $gg \to H$ cross sections $\sigma^{\rm exact}_{\rm NLO/NNLO}$ and the cross section in the effective approach with an infinite top quark mass $\sigma^{m_t \to \infty}_{\rm NLO/NNLO}$. Right: relative difference (in %) between the complete and partial factorisation approaches for the EW radiative corrections to the NLO $gg \to H$ cross section as a function of the Higgs mass.

3 Total uncertainties

The very important issue that remains is how to combine the various theoretical errors on the cross section discussed in the previous section. The CDF collaboration adds quadratically the scale variation (with $\kappa = 2$) with the PDF–error only, leading to a a $10\%(\text{scale}) \oplus 5\%(\text{PDF}) = 11\%$ total error, while D0 collaboration assumes a smaller error of 10%. As these are theoretical errors, we believe that such a combination is not adequate. On the other hand, adding the errors linearly may appear to be too conservative. We thus propose a procedure which, to our opinion, is more reasonable: one calculates the maximal/minimal cross sections with respect to the scale variation, and apply on these cross sections the PDF+$\Delta\alpha_S$ analysis in quadrature, with a final linear addition of the small EFT errors.

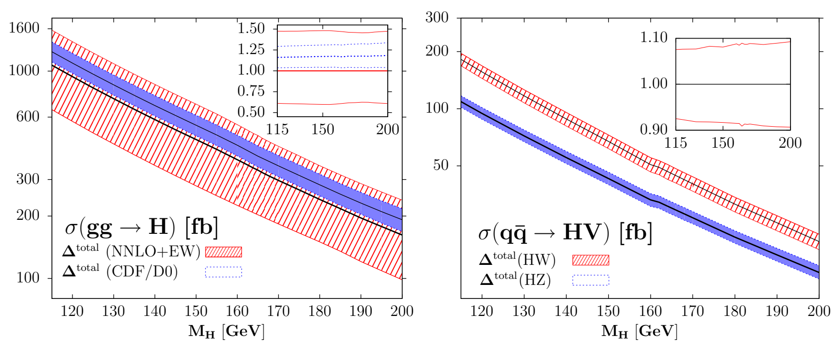

Figure 5: Left: the production cross section $\sigma(gg \to H)$ at NNLO at the Tevatron with the uncertainty band when all the errors are added using our procedure. It is compared to $\sigma(gg \to H)$ at NNLL when the scale and PDF errors given in Ref. [8] are added in quadrature. In the insert the relative deviations are shown when the central values are normalized to $\sigma^{\rm NNLO+EW}$. Right: the same but for the $q\bar{q} \to HV$ production channel.

Using this procedure, we then obtain a total $\simeq \pm 40\%$ uncertainty for the cross section in the gluon–gluon fusion mechanism $gg \to H$ in the entire M_H range that is relevant at the Tevatron; Fig. 5 (left). This error is thus much larger than the $\simeq 10\%$ uncertainty obtained in the CDF/D0 analysis[3]. This means that $\sigma^{\rm NNLO}_{\rm gg \to H}$ could be a factor or two lower than what is assumed in the $p\bar{p} \to H \to W^{(*)}W^{(*)} \to \ell\ell\nu\nu$ analysis and that the 95% CL CDF/D0 exclusion band $162 \leq M_H \leq 166$ GeV should then be reconsidered in the light of these large uncertainties.

We have performed the same analysis in the case of the Higgs–strahlung mechanism $q\bar{q} \to HV$. The total uncertainty, which is the same for WH and ZH production, is about $\simeq \pm 10\%$, with the dominant component coming from the PDF and α_s; the scale error is at the level of a few percent while there is no use of EFT. This total uncertainty is much smaller than the one in the gluon–gluon channel, proving that the Higgs–strahlung mechanism is theoretically much better under control. Nevertheless, the total uncertainty is a factor of two larger than the errors assumed by the CDF/D0 collaborations in their experimental analysis.

Acknowledgments AD would like to thank the Moriond organisers for their invitation and for the very nice and friendly atmosphere during the meeting. This work is supported by the European network HEPTOOLS.

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