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The Tevatron Higgs exclusion limits and theoretical uncertainties

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Summary. — We discuss the exclusion limits set by the CDF and D0 experiments on the Higgs sector from their Higgs boson searches at the Tevatron in the light of large theoretical uncertainties that affect the signal (and background) production cross sections. In the context of the Standard Model, when the theoretical uncertainties stemming from strong (and to a much lesser extent, electroweak) interaction effects are consistently taken into account, the sensitivity of the two experiments becomes significantly lower and the currently excluded Higgs mass range could be entirely reopened. In the Minimal Supersymmetric extension of the Standard Model where the Higgs sector is enlarged to contain two doublet scalar fields, including the theoretical uncertainties will also significantly loosen the constraints obtained at the Tevatron on the supersymmetric Higgs sector parameter space.

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1. – Introduction

The search for the Higgs bosons, the remnants of the spontaneous breaking of the electroweak symmetry that is at the origin of the elementary particle masses, is the main goal of present high-energy colliders. While a single Higgs boson is predicted in the Standard Model (SM), the minimal realization of the symmetry breaking with only one Higgs doublet field [1], the Higgs sector is extended in supersymmetric theories [2], that are widely considered to be the most attractive extensions of the SM as they stabilize the hierarchy between the electroweak and Planck scales induced by the large radiative corrections to the Higgs boson mass. In the minimal extension, the Minimal Supersymmetric Standard Model (MSSM) [2], two Higgs doublet fields are required, leading to the existence of five Higgs particles: two CP-even h and H, a CP-odd A and two charged $H^{\pm}$ particles [3, 4]. With its successful operation in the last years, the Tevatron $p\bar{p}$ collider has now collected a substantial amount of integrated luminosity which allows the CDF and D0 experiments to be sensitive to theses Higgs particles and (for the moment) to set exclusion limits on their masses.

At the Tevatron, the main search channel for the SM Higgs boson is the top and bottom quark loop mediated gluon-gluon fusion mechanism(1) $gg \to H$ with the Higgs boson decaying into WW pairs which lead to the clean $\ell\nu\ell\bar{\nu}$ final states with $\ell = e, \mu$. Strong constraints beyond the well established LEP bounds [5] have been recently set by the CDF and D0 collaborations on the Higgs mass and the range $M_H = 158$–$175\,\mathrm{GeV}$ has been excluded at the 95% confidence level (CL) [6].

Nevertheless, this exclusion limit relies crucially on the theoretical predictions for the cross sections of both the Higgs signal and the relevant SM backgrounds which, as is well known, are affected by significant uncertainties. In recent studies [7, 8], it has been re-emphasized that this is indeed the case for the main Higgs search channel at the Tevatron: adding all sources of theoretical uncertainties in a consistent manner, one obtains an overall uncertainty of about $\pm 40\%$ on the $gg \to H \to \ell\nu\ell\bar{\nu}$ signal(2). This is much larger than the uncertainty assumed in the CDF/D0 analysis, *i.e.* 10% for D0 and 20% for CDF, thus casting some doubts on the resulting exclusion limit.

In this talk, we confront the Tevatron exclusion Higgs limit with the theoretical uncertainties that affect the signal and background rates. We show that when they are included, the sensitivity of the CDF/D0 experiments is significantly lower than the currently quoted one. We find the necessary luminosity that is required to recover the current sensitivities to be substantially higher than the present luminosity. In the case of the MSSM, we also consider the two main production and detection channels: gluon-gluon and bottom quark fusion leading to Higgs bosons (with possibly large rates as a result of enhanced Higgs-$b\bar{b}$ couplings) which subsequently decay into tau leptons, $gg, b\bar{b} \to$ Higgs $\to \tau^+\tau^-$ and show that the theoretical uncertainties will also significantly loosen the constraints obtained on the supersymmetric Higgs sector at the Tevatron.

2. – Theoretical uncertainties

We start by summarizing the impact of the theoretical uncertainties on the $gg \to H$ signal cross section [10] in the SM which has a threefold problem. First, the perturbative QCD corrections to the cross section turned out to be extremely large: the K-factor defined as the ratio of the higher order to the leading order (LO) cross sections, is about a factor of 2 at next-to-leading order (NLO) and about a factor of 3 at next-to-next-to-leading order (NNLO). It is clear that it is this exceptionally large K-factor which presently allows sensitivity to the Higgs at the Tevatron. Nevertheless, the K-factor is so large that one may question the reliability of the perturbative series and the possibility of still large higher order contributions beyond NNLO cannot be excluded.

The effects of the unknown contributions are usually estimated from the variation of the cross section with the (renormalisation μ_R and factorisation μ_F) scale at which the process is evaluated. Starting from a median scale μ_0 which is taken to be $\mu_R = \mu_F = \mu_0 = \frac{1}{2}M_H$ in the $gg \to H$ process, the current convention is to vary these two scales within the range $\mu_0/\kappa \le \mu_R, \mu_F \le \kappa\mu_0$ with the choice $\kappa = 2$. However, as the QCD corrections are so large in the present case, it is wise to extend the domain of scale

(1) The subleading Higgs-strahlung processes $q\bar{q} \to WH, ZH$ add a little to the sensitivity, in particular at low Higgs masses; they will not be discussed here.
(2) There are also uncertainties on the Higgs decay branching ratios, but they are very small in the excluded M_H range; see ref. [9].

variation and adopt instead a value $\kappa = 3$. This is the choice made in ref. [7] which resulted in an $\mathcal{O}(20\%)$ scale uncertainty(^{3}) on $\sigma^{\rm NNLO}_{gg\to H}$.

Another problem that is specific to the $gg \to H$ process is that, already at LO, it occurs at the one-loop level with the additional complication of having to account for the finite mass of the loop particle. This renders the NLO calculation extremely complicated and the NNLO calculation a formidable task. Luckily, one can work in an effective field theory (EFT) approach in which the heavy loop particles are integrated out, making the calculation of the contributions beyond NLO possible. While this approach is justified for the dominant top quark contribution for $M_H \lesssim 2m_t$, it is not valid for the b-quark loop and for those involving the electroweak gauge bosons [12]. The uncertainties induced by the use of the EFT approach at NNLO are estimated to be of $\mathcal{O}(5\%)$ [7].

A third problem is due to the presently not satisfactory determination of the parton distribution functions (PDFs). Indeed, in this gg initiated process, the gluon densities are poorly constrained, in particular in the high Bjorken-x regime which is relevant for the Tevatron. Furthermore, since $\sigma^{\rm LO}_{gg\to H} \propto \alpha_s^2$ and receives large contributions at $\mathcal{O}(\geq \alpha_s^3)$, a small change of α_s leads to a large variation of $\sigma^{\rm NNLO}_{gg\to H}$. Related to that is the significant difference between the world average α_s value and the one from deep-inelastic scattering (DIS) data used in the PDFs [13]. There is a statistical method to estimate the PDF uncertainties by allowing a 1σ (or more) excursion of the experimental data that are used to perform the global fits. In addition, the MSTW collaboration [14] provides a scheme that allows for a combined evaluation of the PDF uncertainties and the (experimental and theoretical) ones on α_s. In ref. [7], the combined 90% CL PDF + $\Delta^{\rm exp}\alpha_s + \Delta^{\rm th}\alpha_s$ uncertainty on $\sigma^{\rm NNLO}_{gg\to H}$ at the Tevatron, was found to be of order 15%. However, this method does not account for the theoretical assumptions that enter into the parametrization of the PDFs. A way to access this theoretical uncertainty is to compare the results for the central values of the cross section with the best-fit PDFs when using different parameterizations.

On the left-hand side of fig. 1 are displayed the values of $\sigma^{\rm NNLO}_{gg\to H}$ obtained when using the gluon densities that are predicted by the four PDF sets that have parameterizations at NNLO: MSTW [14], JR [15], ABKM [16] and HERAPDF [17]. As can be seen, there is a very large spread in the four predictions, in particular at large M_H where the poorly constrained gluon densities at high-x are involved. The largest rate is obtained with MSTW, but the cross section using the ABKM(^{4}) set is $\approx$ 25%–30% lower than that [18].

A related issue, which is of utmost importance, is the way these various uncertainties should be combined. The CDF and D0 experiments simply add in quadrature the uncertainties from the scale variation and the PDF uncertainties obtained through the Hessian method (and ignore the smaller EFT uncertainty) and they obtain an overall uncertainty of order 20% on the inclusive cross section. We believe (see also ref. [19]) that this procedure has no justification(^{5}). Indeed, the uncertainties associated to the PDFs

(^{3}) See also ref. [11] for another reason to increase the scale uncertainty to 20%.

(^{4}) In an earlier version of ref. [8], an error resulted in a HERAPDF prediction that was $\approx$ 40% lower than that of MSTW. We thank Graham Watt for pointing to us the problem.

(^{5}) There were some responses to the addendum of ref. [7] from CDF and D0 on the `tevnphwg.fnal.gov` web site. While many comments were made on secondary and/or agreed points, the main issue (which explains the difference between our results) is the way to combine the scale and PDF uncertainties, and it was not really addressed.

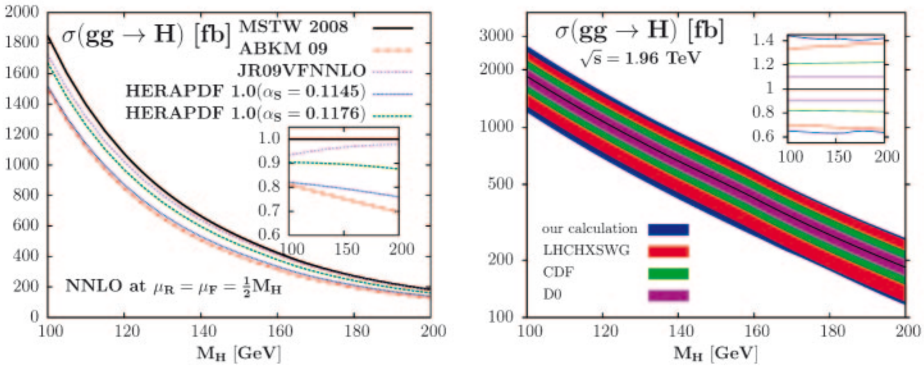

Fig. 1. – Left: the $gg \to H$ cross section as a function of M_H when the four NNLO PDF sets, MSTW, ABKM, JR and HERAPDF, are used; in the inserts, shown are the deviations with respect to the central MSTW value. Right: $\sigma^{\rm NNLO}_{gg\to H}$ at the Tevatron using the MSTW PDFs, with the uncertainty band when all theoretical uncertainties are added as in ref. [7] (BD); it is compared the uncertainties quoted by the CDF and D0 experiments [6] as well as the uncertainty when the LHC procedure [20] is adopted; in the insert, the relative size of the uncertainties compared to the central value are shown.

in a given scheme should be viewed as purely theoretical uncertainties (due to the theoretical assumptions in the parameterization) despite of the fact that they are presented as the 1σ or more departure from the central values of the data included in the PDF fits. In some sense, they should be equivalent to the spread that one observes when comparing different parameterizations of the PDFs. Thus, the PDF uncertainties should be considered as having no statistical ground (or a flat prior in statistical language), and thus, combined linearly with the uncertainties from the scale variation and the EFT approach, which are pure theoretical errors. This is the procedure recommended, for instance, by the LHC Higgs cross section working group [20]. Another, almost equivalent, procedure has been proposed in ref. [7]: one applies the combined PDF-α_s uncertainties directly on the maximal/minimal cross sections with respect to scale variation([6]), and then adds linearly the small uncertainty from the EFT approach. This last procedure, that we have used here, provides an overall uncertainty that is similar (but slightly smaller) to that obtained with the linear sum of all uncertainties.

The overall theoretical uncertainty on $\sigma^{\rm NNLO}_{gg\to H}$ that is obtained this way, using MSTW PDFs, is shown on the right-hand side of fig. 2. In the mass range $M_H \approx 160\,\text{GeV}$ with almost the best sensitivity, one obtains a $\approx +41\%$, -37% total uncertainty, to be compared to the $\approx 10\%$ and $\approx 20\%$ uncertainties assumed, respectively, by the CDF and D0 collaborations. We also show for comparison, the result obtained when one adds linearly, *i.e.* as recommended by the LHC Higgs cross section working group, the uncertainties from scale ($+20\%$, -17% on the sum of the jet cross sections([7])) and PDFs

([6]) A similar procedure has also been advocated in ref. [21] for top quark pair production.
([7]) An additional uncertainty of $\approx 7.5\%$ from jet acceptance is introduced when considering the Higgs+jet cross sections. We will consider it to be experimental and, when added in quadrature to others, will have little impact.

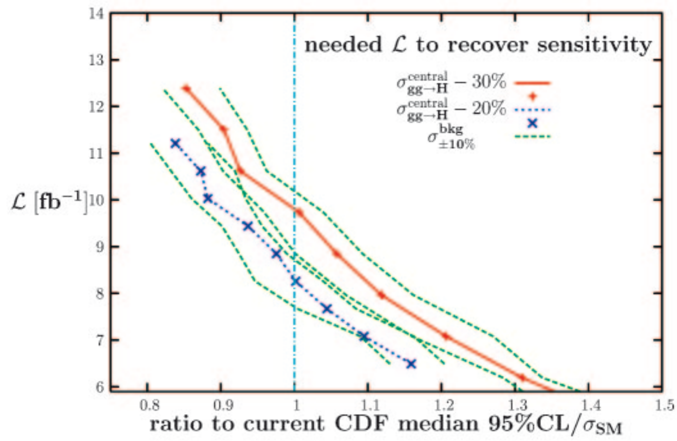

Fig. 2. – The luminosity needed by the CDF experiment to recover the current sensitivity (with $5.9\,\text{fb}^{-1}$ data) when the $gg \to H \to \ell\ell\nu\nu$ signal rate is lowered by 20 and 30% and with a $\pm 10\%$ change in the $p\bar{p} \to WW$ dominant background.

($+16\%$, -15% when the MSTW 68% CL PDF + $\Delta^{\rm exp}\alpha_s$ error is multiplied by a factor of two following the PDF4LHC recommendation), leading to a total of $\approx +36\%$, -32% for $M_H \approx 160\,\text{GeV}$. Thus, the uncertainty that we assume is comparable to the one obtained using the LHC procedure [20], the difference being simply due to the additional $\mathcal{O}(5\%)$ uncertainty from the use of the EFT approach that we also include.

3. – Emulation of the Tevatron limit

Let us now come to the discussion of the Higgs Tevatron exclusion limit in the light of these theoretical uncertainties. We base our exploration on a CDF study [22] which provides us with all the necessary details. In the analysis of the $gg \to H \to WW \to \ell\ell\nu\nu$ signal, the cross section has been broken into the three pieces which yield different final state signal topologies, namely $\ell\ell\nu\nu + 0$ jet, $\ell\ell\nu\nu + 1$ jet and $\ell\ell\nu\nu + 2$ jets or more. These channels which represent, respectively, $\approx 60\%$, $\approx 30\%$ and $\approx 10\%$ of the total $\sigma^{\rm NNLO}_{gg\to H}$ [19], have been studied separately (other channels are irrelevant in practice). Our main goal is to estimate the necessary relative variation of the integrated luminosity needed to reproduce the currently quoted sensitivity of the CDF collaboration, if the normalization of the Higgs signal cross section (as well as the corresponding backgrounds) is different from the one assumed to obtain the results. Our approach consists of the following.

First, we try to reproduce as closely as possible the CDF results using the information given in ref. [22] for a mass $M_H = 160\,\text{GeV}$, for which the sensitivity is almost the best (we will assume that the results are similar in the entire excluded mass range $M_H \approx$ 158–175 GeV). Then, we consider scenarios in which the *normalisation* of the Higgs production cross section is reduced. We estimate the *relative variation* of the sensitivity and increase the integrated luminosity until we recover our initial sensitivity. Finally, we assume that the obtained relative variations of the sensitivity as well as the required luminosity to reproduce the initial sensitivity, would be the same for the CDF experiment.

To be as close as possible to the CDF analysis and results [22], we considered their neural network outputs for all the search channels (each one for the signals, backgrounds and data) to build the background only and the background plus signal hypotheses, implemented them in the program `MClimit` [23] and used a ratio of log-likelihood "*à la* LEP" as a test-statistic for which we combined the above channels; this provided the 95% CL/$\sigma_{\rm SM}$ sensitivity limit on the Higgs boson at the considered mass of $M_H = 160\,$GeV. We obtain median expected and expected 95% CL/$\sigma_{\rm SM}$ limits that are satisfactorily close to the those in the CDF analysis.

We consider two scenarios in which the $gg \to H \to WW \to \ell\ell\nu\nu$ signal cross section has been reduced by 20% and 30%. The first one is to account for the difference between the quadratic and (almost) linear ways of combining the individual uncertainties. The second scenario, would be simply to adopt the normalisation obtained using the ABKM PDFs which gives a $\approx 30\%$ reduction of $\sigma^{\rm NNLO}_{gg\to H}$. In both cases, the remaining $\approx 20\%$ uncertainty due to scale variation and the EFT will correspond to the overall theoretical uncertainty that has been assumed in the Tevatron analysis.

In each case, the expected signals and the corresponding backgrounds at the Tevatron have been multiplied by a luminosity factor that has been varied. For each value of the luminosity factor, the corresponding median expected 95% CL/$\sigma_{\rm SM}$ has been estimated and normalized to the initial sensitivity $S_0 = 1.35$ obtained above. The results are reported in fig. 2 where the Tevatron luminosity is shown as a function of the obtained normalised sensitivity. One sees that if $\sigma^{\rm NNLO}_{gg\to H}$ is lowered by 20%, a luminosity of $\approx 8\,{\rm fb}^{-1}$, compared to $5.9\,{\rm fb}^{-1}$ used in [22] would be required for the same analysis to obtain the current sensitivity. If the rate is lower by 40% (as it was the case with our incorrect HERAPDF cross section), the required luminosity should increase to $\approx 13\,{\rm fb}^{-1}$, *i.e.* more than a factor of two, to obtain the present CDF sensitivity.

As an additional exercise, we also analyzed the impact of changing the normalization of the background rate by $\pm 10\%$ simultaneously with lowering the signal rate (the correlation between signal and background is implicitly taken into account as we use the results of [22]; we assume though that it is almost the same when another PDF set is adopted). Indeed, it is clear that one should equally consider the same uncertainties in the cross sections of the backgrounds, the by far largest one being $p\bar{p} \to W^+W^-$. We have evaluated it and found that the uncertainty, when evaluated according to ref. [7], is $\approx 10\%$ larger that what CDF/D0 assume. In addition, if we adopt the ABKM set, one would obtain a rate that is $\approx 10\%$ higher than with MSTW [18]. We will thus consider that $\sigma(p\bar{p} \to W^+W^-)$ can be $\approx 10\%$ larger/lower than assumed by CDF/D0 and we will consider a third scenario in which the normalization of the $p\bar{p} \to WW$ background is changed by $\pm 10\%$.

From fig. 2, one clearly sees that increasing/decreasing the background will degrade/improve the sensitivity and a $\approx 10\%$ higher/lower luminosity would be required to recover the sensitivity. Hence, the reduction of the signal by 30% and the increase of the background by 10%, as would be the case if the ABKM PDFs were used for their normalization, would reopen a large part of the mass range $M_H = 158$–$175\,$GeV excluded by the CDF/D0 analysis with $12.6\,{\rm fb}^{-1}$ combined data. Hence, we face the uncomfortable situation in which the Higgs exclusion limit depends on the considered PDF.

4. – The case of the MSSM

While a single Higgs boson is predicted in the SM, the Higgs sector is extended in supersymmetric theories [2] to contain five Higgs particles: two [3, 4]. Two parameters are needed to describe the Higgs sector at tree-level: the mass M_A of the pseudoscalar boson and the ratio of vacuum expectation values of the two Higgs fields, $\tan\beta$, that is

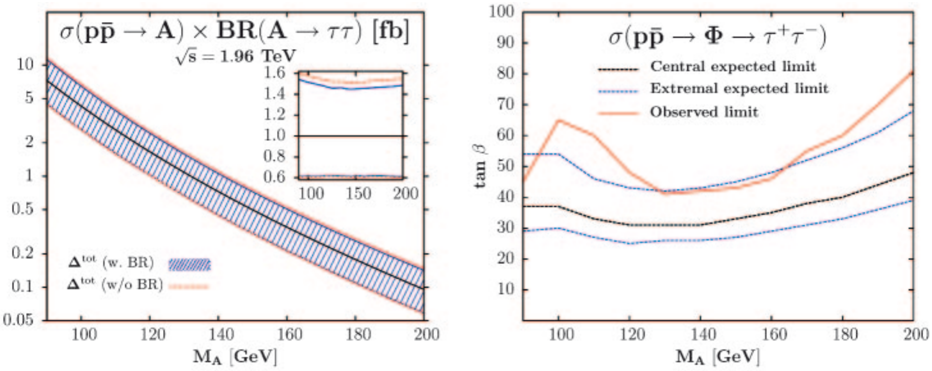

Fig. 3. – Left: $\sigma(p\bar{p} \to A) \times \mathrm{BR}(A \to \tau^+\tau^-)$ as a function of M_A at the Tevatron, together with the associated overall theoretical uncertainty. Right: contours for the expected $\sigma(p\bar{p} \to \Phi \to \tau^+\tau^-)$ rate at the Tevatron in the $[M_A, \tan\beta]$ plane with the associated theory uncertainties, confronted to the 95% CL exclusion limit.

expected to lie in the range $1 \lesssim \tan\beta \lesssim 50$. At high $\tan\beta$ values, $\tan\beta \gtrsim 10$, one of the neutral CP-even states has almost exactly the properties of the SM Higgs particle: its couplings to fermions and gauge bosons are the same, but its mass is restricted to values $M_H^{\max} \approx 110$–$135\,\mathrm{GeV}$ depending on some SUSY parameters that enter the radiative corrections [4]. The other CP-even and the CP-odd states, that we will denote collectively by $\Phi = A, H(h)$, are then almost degenerate in mass and have the same properties: no couplings to gauge bosons, while the couplings to isospin down-type (up-type) quarks and charged leptons are (inversely) proportional to $\tan\beta$.

Thus, for $\tan\beta \gtrsim 10$, the Φ boson couplings to bottom quarks and τ-leptons are strongly enhanced while those to top quarks are suppressed. As a result, the phenomenology of these states becomes rather simple. To a very good approximation, the Φ bosons decay almost exclusively into $b\bar{b}$ and $\tau^+\tau^-$ pairs with branching ratios of, respectively, $\approx 90\%$ and $\approx 10\%$, while the other decay channels are suppressed to a negligible level [24]. The main production mechanisms for these particles are those processes which involve the couplings to bottom quarks. At hadron colliders, these are the gluon-gluon fusion mechanism, $gg \to \Phi$, which dominantly proceeds through b-quark triangular loops [25] and bottom-quark fusion, $b\bar{b} \to \Phi$ [26], in which the bottom quarks are directly taken from the protons in a five active flavor scheme. The latter process is similar to the channel $p\bar{p} \to b\bar{b}\Phi$ when no b-quarks are detected in the final state [27].

In ref. [28], we have updated the cross sections for the production of the MSSM CP-odd like Higgs bosons Φ at the Tevatron in the processes $gg \to \Phi$ and $b\bar{b} \to \Phi$ and found smaller rates in the high Higgs mass range compared to those assumed by the Tevatron experiments [29]. We have then evaluated the associated theoretical uncertainties, including also the ones in the $\Phi \to \tau^+\tau^-$ branching fractions, and find that they are very large; see the left-hand side of fig. 3. These uncertainties, together with the correct normalization, affect significantly the exclusion limits set on the MSSM parameter space from the negative Higgs searches in the channel $p\bar{p} \to \Phi \to \tau^+\tau^-$ at the Tevatron.

To visualize the impact of these theoretical uncertainties on the MSSM $[M_A, \tan\beta]$ parameter space that is probed when searching experimentally for the $p\bar{p} \to \Phi \to \tau^+\tau^-$ channel, we show on the right-hand side of fig. 3 the contour of the cross section times branching ratio in this plane, together with the contours when the uncertainties are included. We apply the model independent 95% CL expected and observed limits from the CDF/D0 analysis [29]. However, rather than applying the limits on the central $\sigma \times \mathrm{BR}$ rate, we apply them on the minimal one when the theory uncertainty is included. Indeed, since the latter has a flat prior, the minimal $\sigma \times \mathrm{BR}$ value is as respectable and likely as the central value. One observes then that only values $\tan\beta \gtrsim 50$ are excluded in the mass ranges, $M_\Phi \approx 95$–$125\,\mathrm{GeV}$ and $M_\Phi \gtrsim 165\,\mathrm{GeV}$. In the intermediate range $M_\Phi \approx 125$–$165\,\mathrm{GeV}$, the exclusion limit is $\tan\beta \gtrsim 40$–45, to be contrasted with the values $\tan\beta \gtrsim 30$ excluded in the CDF/D0 analysis. Hence, the inclusion of the theory uncertainties has a drastic impact on the allowed $[M_A, \tan\beta]$ parameter space.

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