Higgs and SUSY Particle Production at Hadron Colliders*

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Abstract

The theoretical status of Higgs boson and supersymmetric particle production at hadron colliders is reviewed with particular emphasis on recent results and open problems.

1 Introduction

Supersymmetry imposes a new symmetry between the fermionic and bosonic degrees of freedom [1]. Since supersymmetric theories do not develop quadratic divergences in higher orders, they provide a natural solution of the hierarchy problem at the electroweak scale [2]. If supersymmetric grand unified theories (SUSY-GUT) are considered, the predicted value of the Weinberg angle turns out to be in excellent agreement with the present measurements at the LEP and SLC experiments [3]. Moreover, owing to the large top quark mass SUSY-GUTs develop electroweak symmetry breaking at the electroweak scale dynamically [4]. Due to these properties the supersymmetric extension of the Standard Model exhibits one of the most attractive alternatives beyond the Standard Model.

The Higgs mechanism is a cornerstone of the Standard Model (SM) and its supersymmetric extensions [5]. Thus, the search for Higgs bosons is one of the most important endeavors at future high-energy experiments. The minimal supersymmetric extension of the Standard Model (MSSM) requires the introduction of two Higgs doublets in order to preserve supersymmetry. There are five elementary Higgs particles, two CP-even (h, H), one CP-odd (A) and two charged ones $(H^\pm)$. At lowest order all couplings and masses of the MSSM Higgs sector are fixed by two independent input parameters, which are generally chosen as $\tan\beta = v_2/v_1$, the ratio of the two vacuum expectation values $v_{1,2}$, and the pseudoscalar Higgs-boson mass M_A. At LO the light scalar Higgs mass M_h has to be smaller than the Z-boson mass M_Z. Including the one-loop and dominant two-loop corrections the upper bound is increased to $M_h \lesssim 135$ GeV [6]. The negative direct searches for the Higgsstrahlung processes $e^+e^- \to Zh, ZH$ and the associated production $e^+e^- \to Ah, AH$ yield lower bounds of $m_{h,H} > 91.0$ GeV and $m_A > 91.9$ GeV. The range $0.5 < \tan\beta < 2.4$ in the MSSM is excluded by the Higgs searches at the LEP2 experiments [7].

Higgs bosons can be searched for at the upgraded Tevatron, a $p\bar{p}$ collider with a c.m. energy of 2 TeV, and the LHC, a pp collider with a c.m. energy of 14 TeV. At the Tevatron the most important processes are Higgs-strahlung $q\bar{q} \to W + h/H$ with $h/H \to b\bar{b}$ which is important for Higgs masses below about 130 GeV, gluon fusion $gg \to h/H \to W^*W$ which is relevant for Higgs masses above 130 GeV, and Higgs radiation off bottom quarks

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$q\bar{q} \to b\bar{b}\phi$ which plays an important rôle for large values of $\tan\beta$. With an integrated luminosity of 30 fb^{-1} the Tevatron can probe the entire MSSM parameter space [8]. At the LHC the most important Higgs production modes are gluon fusion, vector boson fusion $qq \to qq + h/H$ and Higgs radiation off top and bottom quarks. There are several Higgs decay modes which enable the discovery of the Higgs bosons [9].

The novel colored particles, squarks and gluinos, and the weakly interacting gauginos can be searched for at the Tevatron and the LHC. Until now the search at the Tevatron has set the most stringent bounds on the colored SUSY particle masses. At the 95% CL, gluinos have to be heavier than about 180 GeV, while squarks with masses below about 180 GeV have been excluded for gluino masses below $\sim$ 300 GeV [10]. Stops, the scalar superpartners of the top quark, have been excluded in a significant part of the MSSM parameter space with mass less than about 80–100 GeV by the LEP [11] and Tevatron experiments [10]. Finally charginos with masses below about 100 GeV have been excluded by the LEP experiments [11], while the present search at the Tevatron is sensitive to chargino masses of about 60–80 GeV with a strong dependence on the specific model [12]. Due to the negative search at LEP2 the lightest neutralino $\tilde{\chi}_1^0$ has to be heavier than about 45 GeV in the context of SUGRA models [11]. In the R-parity-conserving MSSM, supersymmetric particles can only be produced in pairs. All supersymmetric particles will decay to the lightest supersymmetric particle (LSP), which is most likely to be a neutralino, stable thanks to conserved R-parity. Thus the final signatures for the production of supersymmetric particles will mainly be jets, charged leptons and missing transverse energy, which is carried away by neutrinos and the invisible neutral LSP.

2 Higgs boson production

2.1 Gluon fusion

The gluon fusion mechanism $gg \to \phi$ provides the dominant production mechanism of Higgs bosons at the LHC in the entire relevant mass range up to about 1 TeV for small and moderate values of $\tan\beta$ in the MSSM [13]. At the Tevatron this process plays a rôle for Higgs masses between about 130 GeV and 190 GeV, if the branching ratio of decays into W^*W pairs is large enough [8]. The gluon fusion process is mediated by heavy quark triangle loops and, in the case of supersymmetric theories, by squark loops in addition, if the squark masses are smaller than about 400 GeV [14].

In the past the full two-loop QCD corrections have been determined. They increase the production cross sections by 10–90% [15, 16], thus leading to a significant change of the theoretical predictions. Very recently, the full NNLO calculation has been finished in the heavy top quark limit [17]. This limit has been demonstrated to approximate the full massive K factor at NLO within about 20% for small $\tan\beta$ in the entire mass range up to 1 TeV [18]. Thus, a similar situation may be expected at NNLO. The reason for the quality of this approximation is that the QCD corrections to the gluon fusion mechanism are dominated by soft and collinear gluon effects, which do not resolve the one-loop Higgs coupling to gluons. Fig. 1 shows the resulting K-factors at the LHC and the scale variation of the K-factor for the SM Higgs boson. The calculation stabilizes at NNLO, with remaining scale variations at the 10–15% level. These uncertainties are comparable to the experimental errors which can be achieved with 300 fb^{-1} of data at the LHC [9]. The full NNLO results confirm earlier estimates which were obtained in the frame work of soft gluon resummation [18] and soft approximations [19] of the full three-loop result within 10–15%. The full soft gluon resummation has been performed in Ref. [20]. The resummation effects enhance the NNLO result further by about 10% thus signaling a perturbative stabilization of the theoretical prediction for the gluon-fusion cross section.

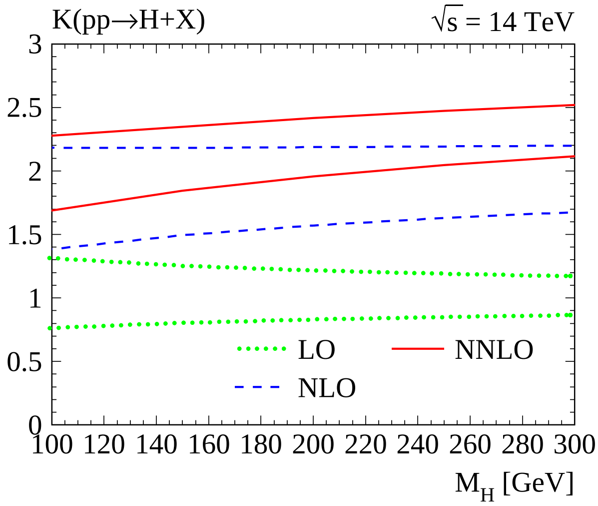

Figure 1: *Scale dependence of the K-factor at the LHC. Lower curves for each pair are for $\mu_R = 2M_H$, $\mu_F = M_H/2$, upper curves are for $\mu_R = M_H/2$, $\mu_F = 2M_H$. The K-factor is computed with respect to the LO cross section at $\mu_R = \mu_F = M_H$. From Ref. [17].*

In supersymmetric theories the gluon fusion cross sections for the heavy Higgs, H, and, for small M_A, also for the light Higgs, h, are significantly affected by bottom quark loops for $\tan\beta \gtrsim 3$ so that the heavy top quark limit is not applicable in general. This can be clearly seen in the NLO results, which show a decrease of the K factor down to about 1.1 for large $\tan\beta$ [16]. This decrease originates from an interplay between the large positive soft/collinear gluon effects and large negative double logarithms of the ratio between the Higgs and bottom masses. In addition, the shape of the p_T distribution of the Higgs boson may be altered; if the bottom loop is dominant, the p_T spectrum becomes softer than in the case of top-loop dominance. These effects lead to some model dependence of predicted cross sections.

2.2 $t\bar{t}\phi$ production

SM Higgs boson production in association with $t\bar{t}$ pairs plays a significant rôle at the LHC for Higgs masses below about 130 GeV, since this production mechanism makes the observation of $H \to b\bar{b}$ possible [9, 21]. The decay $H \to \gamma\gamma$ is potentially visible in this channel at high integrated luminosity. For Higgs masses above about 130 GeV, the decay $H \to W^*W$ can be observed [22]. $t\bar{t}H$ production could conceivably be used to determine the top Yukawa coupling directly from the cross section. NLO QCD corrections have become available. They decrease the cross section at the Tevatron by about 20% [23, 24], while they increase the signal rate at the LHC by about 20–40% [23], see Fig. 2. The scale dependence of the production cross section is significantly reduced, to a level of about 10–15%, which can be considered as an estimate of the theoretical uncertainty.

The transverse momentum and rapidity distributions at NLO can be approximated by a rescaling of the LO distributions with a constant K factor within 10–15% [25]. Thus, the signal rate is under proper theoretical control now. In the MSSM, $t\bar{t}h$ production with $h \to \gamma\gamma, b\bar{b}$ is important at the LHC in the decoupling regime, where the light scalar h behaves as the SM Higgs boson [9, 21]. Thus, the SM results can also be used for $t\bar{t}h$ production in this regime.

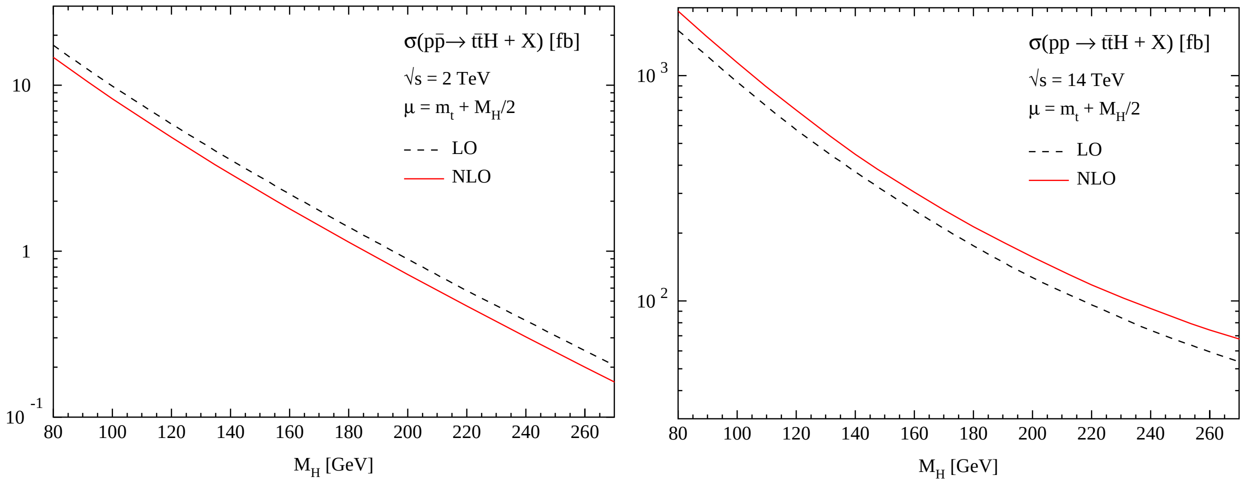

Figure 2: *The cross section for* $pp/p\bar{p} \to t\bar{t}H + X$ *at the Tevatron and LHC in LO and NLO approximation, with the renormalization and factorization scales set to* $\mu = m_t + M_H/2$.

2.3 $b\bar{b}\phi$ production

In supersymmetric theories $b\bar{b}\phi$ production becomes the dominant Higgs boson production mechanism for large values of $\tan\beta$ [13], where the bottom Yukawa coupling is strongly enhanced. In contrast to $t\bar{t}\phi$ production, however, this process develops potentially large logarithms, $\log m_\phi^2/m_b^2$, in the high-energy limit due to the smallness of the bottom quark mass, which are related to the development of b densities in the initial state. They can be resummed by evolving the b densities according to the DGLAP–equations and introducing them in the production process [26]. The NLO QCD corrections to the b-initiated processes $b\bar{b} \to H$ [27] and $\overset{(-)}{b}g \to \overset{(-)}{b}H$ [28] are known to be moderate. The resummation increases the cross section by a factor of about 5 at the Tevatron and about 2–3 at the LHC and thus plays a significant phenomenological rôle. The introduction of conventional b densities, however, requires an approximation of the hard process kinematics, i.e. the initial and final b quarks are assumed to be massless and travel predominantly in forward and backward direction. These approximations can be tested in the full $gg \to b\bar{b}\phi$ process.

We have to investigate if the energy of the Tevatron and LHC is sufficiently large to develop the factorization of bottom densities, i.e. that the transverse mass distribution of the (anti)bottom quark can be factorized as a convolution

$$\frac{d\sigma}{dM_{Tb}} = \frac{1}{M_{Tb}} \left\{ \frac{\alpha_s}{2\pi} P_{qg} \otimes g \otimes g \otimes \hat{\sigma}_{bg} \right\}_{M_{Tb}=m_b \to 0} + \text{non-singular terms} \qquad (1)$$

where $M_{Tb} = \sqrt{m_b^2 + p_{Tb}^2}$ denotes the transverse mass of the (anti)bottom quark, P_{qg} the corresponding DGLAP splitting kernel, g the gluon density of the (anti)proton and $\hat{\sigma}_{bg}$ the partonic cross section for $\overset{(-)}{b} g \to \overset{(-)}{b} H$. This factorization requires that the transverse mass distribution is dominated by the first term, i.e. $d\sigma/dM_{Tb} \propto 1/M_{Tb}$, for transverse masses up to the factorization scale of the (anti)bottom density. The transverse mass

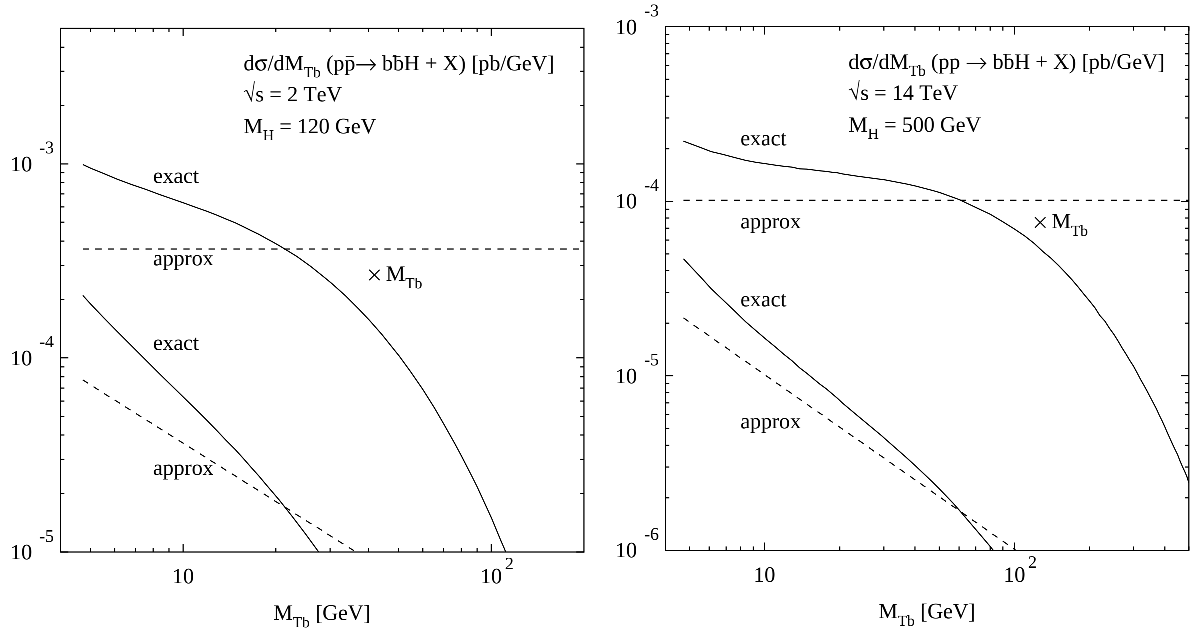

Figure 3: *Transverse mass distributions of the bottom quark in $b\bar{b}H$ production at the Tevatron and the LHC. We have adopted CTEQ5M1 parton densities and a bottom mass of $m_b = 4.62$ GeV. The solid lines show the full LO result from $q\bar{q}, gg \to b\bar{b}H$ and the dashed lines the factorized collinear part of Eq. (1) which is absorbed in the bottom parton density. The upper curves are multiplied with the factor M_{Tb} of the asymptotic behavior, which is required by factorizing bottom densities.*

distributions at the Tevatron and LHC are shown in Fig. 3. The solid curves show the full distributions of the $q\bar{q}, gg \to b\bar{b}\phi$ processes, while the dashed lines exhibit the factorized collinear part of Eq. (1) which is absorbed in the bottom density. For a proper factorization, these pairs of curves have to coincide approximately up to transverse masses of the order of the factorization scale, which is usually chosen to be $\mu_F = \mathcal{O}(m_H)$. It is clearly visible that there are sizeable differences between the full result and the factorized part, which originate from sizeable bottom mass and phase space effects, that are not accounted for by an active bottom parton density. Moreover, the full result falls quickly below the approximate factorized part for transverse masses of the order of $m_H/10$, which is much smaller than the usual factorization scale used for the bottom densities. We conclude from these plots that $b\bar{b}\phi$ production at the Tevatron and LHC develops sizeable bottom mass and kinematical phase space effects, so that the use of bottom densities in the process $b\bar{b} \to \phi$ may lead to an overestimate of the correct theoretical result due to too crude approximations in the kinematics of the hard process [29]. The full NLO calculation of the $gg \to b\bar{b}\phi$ will yield much more insight into this problem, since the large logarithms related to the evolution of bottom densities have to appear in the NLO corrections, if the picture of active bottom quarks in the proton is correct.

3 SUSY particle production

3.1 Production of squarks and gluinos

Squarks and gluinos can be produced via $pp, p\bar{p} \to \tilde{q}\bar{\tilde{q}}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ at hadron colliders. The determination of the full SUSY–QCD corrections has been performed for the upgraded Tevatron and the LHC. For the natural renormalization/factorization scale choice $Q = m$, where m denotes the average mass of the final-state SUSY particles, the SUSY QCD corrections are large and positive, increasing the total cross sections by 10–90% [30]. The inclusion of the NLO corrections reduces the LO scale dependence by a factor 3–4 and reaches a typical level of $\sim$ 10–15% which serves as an estimate of the remaining theoretical uncertainty. Moreover, the dependence on different sets of parton densities is rather weak and leads to an additional uncertainty of $\sim$ 10–15%. In order to quantify the effect of the NLO corrections on the search for squarks and gluinos at hadron colliders, the SUSY particle masses corresponding to several fixed values of the production cross sections have been extracted. These masses are increased by 10–30 GeV at the Tevatron and 10–50 GeV at the LHC, thus enhancing the present and future bounds on the squark and gluino masses significantly. Finally, the QCD-corrected transverse-momentum and rapidity distributions for all different processes have been evaluated. The modification of the normalized distributions in NLO compared to LO is less than about 15% for the transverse-momentum distributions and much less for the rapidity distributions. Thus it is a sufficient approximation to rescale the LO distributions uniformly by the K factors of the total cross sections [30].

3.2 Stop pair production

At LO only pairs of $\tilde{t}_1$ or pairs of $\tilde{t}_2$ can be produced at hadron colliders. QCD-initiated mixed $\tilde{t}_1\tilde{t}_2$ pair production is only possible at NLO and beyond. However, mixed stop pair production is completely suppressed by several orders of magnitude and can thus safely be neglected [31]. The evaluation of the SUSY–QCD corrections proceeds along the same lines as in the case of squarks and gluinos. They increase the total cross sections by up to about 40% [31]. As in the squark/gluino case the scale dependence is strongly reduced and yields an estimate of about 10–15% of the remaining theoretical uncertainty at NLO. At NLO the virtual corrections depend on the stop mixing angle, the squark, gluino and stop masses of the other type. However, it turns out that these dependences are very weak and can safely be neglected.

3.3 Chargino and neutralino production

The production cross sections of charginos and neutralinos depend on several MSSM parameters, i.e. M_1, M_2, μ and $\tan\beta$ at LO [32]. The cross sections are sizeable for chargino/neutralino masses below about 100 GeV at the upgraded Tevatron and less than about 200 GeV at the LHC. Due to the strong dependence on the MSSM parameters the extracted bounds on the chargino and neutralino masses depend on the specific region in the MSSM parameter space [10]. The outline of the determination of the SUSY–QCD corrections is analogous to the previous cases of squarks, gluinos and stops. The corrections enhance the production cross sections of charginos and neutralinos by about 10–40% [33]. The scale dependence is reduced to about 10% at NLO, which signalizes a significant stabilization of the theoretical prediction for the production cross sections. The dependence of the chargino/neutralino production cross sections on the specific set of parton densities ranges at about 10–15% [33].

3.4 Associated production of gluinos and gauginos

The cross sections of the associated gluino-gaugino production are sizeable for the lightest chargino/neutralino states at the upgraded Tevatron and the LHC if the gluino mass is less than about 400–500 GeV [32]. The determination of the SUSY–QCD corrections is analogous to the previous cases of squarks, gluinos, stops and gauginos. The production cross sections are decreased by up to 3% at the Tevatron and increased by about 10–20% at the LHC due to these corrections [35] as can be inferred from Fig. 4[†]. The scale de-

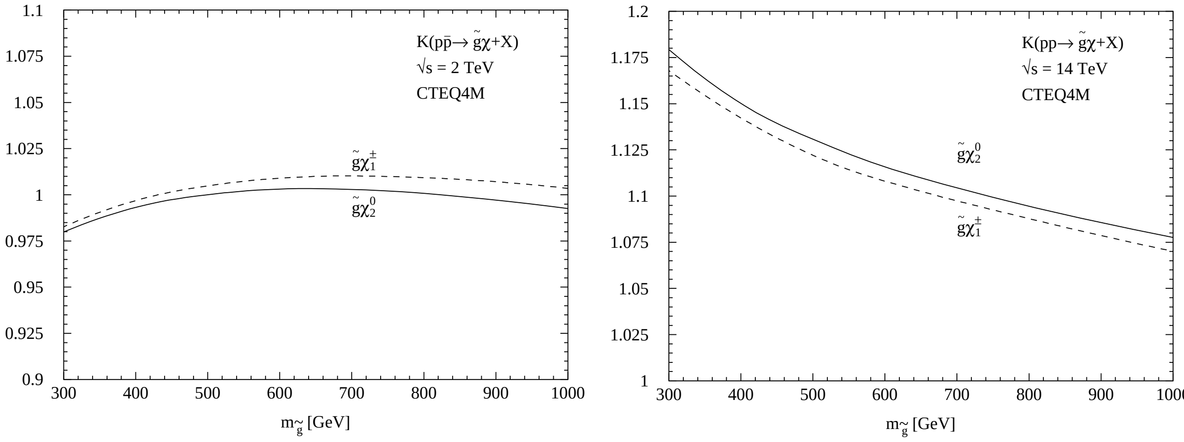

Figure 4: *K factor of the cross sections for gluinos produced in association with the gauginos χ_2^0 and $\chi_1^\pm$ at the upgraded Tevatron (left) and the LHC (right). Parton densities: CTEQ4L (LO) and CTEQ4M (NLO) with the renormalization/factorization scale $Q = (m_{\tilde{g}} + m_\chi)/2$.*

pendence is shown in Fig. 5 at LO and NLO. It is clearly visible that it is reduced to about 10–15% at NLO which signalizes a significant stabilization of the theoretical prediction for the production cross sections. The dependence of the gluino-gaugino production cross sections on the specific set of parton densities ranges at about 10–15% [35].

4 Conclusions

Considerable progress has been made recently in improving QCD calculations for Higgs and supersymmetric signal cross sections at hadron colliders. Most (N)NLO [SUSY–]QCD

[†] These results disagree with Ref. [34]. After discrepancies could be resolved in the virtual corrections and for the qg initial state, the residual unresolved discrepancies are associated with the hard-gluon radiation part of the $q\bar{q}$ channel. We have performed the analysis by means of two completely independent methods – phase space slicing as well as the massive extension of the dipole subtraction formalism [36]. The results we have obtained for the two methods, are in perfect agreement with each other so that their validity is beyond any resonable doubt.

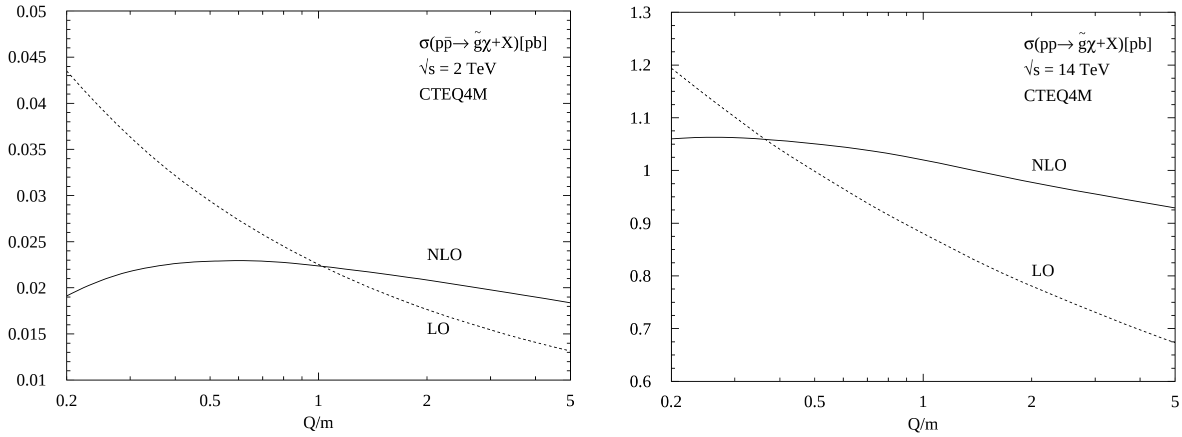

Figure 5: *Scale dependence of the cross sections of gluinos produced in association with* χ_2^0 *at the upgraded Tevatron (left) and the LHC (right). Parton densities: CTEQ4L (LO) and CTEQ4M (NLO) with the renormalization/factorization scale Q varied in units of the average mass* $m = (m_{\tilde{g}} + m_\chi)/2$.

corrections to all relevant production processes at hadron colliders are known, i.e. the theoretical status of novel particle production at the Tevatron and LHC is nearly complete. Large corrections to many processes have been found which underlines the importance of including them in realistic experimental analyses. After inclusion of the NLO corrections the residual theoretical uncertainties are reduced to a level of 10–15%. There are several Fortran programs which include most of the higher order corrections [37].

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