UAB-FT-471
KA-TP-13-1999
hep-ph/9909397
September 1999

Top quark and charged Higgs at the Tevatron-Run II[1]

J.A. Coarasa[a], Jaume Guasch[b], Joan Solà[a]

[a]*Grup de Física Teòrica and Institut de Física d'Altes Energies, Universitat Autònoma de Barcelona, E-08193, Bellaterra, Barcelona, Catalonia, Spain*

[b]*Institut für Theorestische Physik, Universität Karlsruhe, D-76128 Karlsruhe, Germany*

ABSTRACT

We shortly review the top quark decay into charged Higgs, and present new results on its production at the upgraded Tevatron. We have computed the MSSM cross-section for single charged Higgs in association with the top quark beyond the regime of on-shell $t\,\bar{t}$ production followed by the decay $t \to H^+\,b$,. Our results are higher than recent results in the literature. In the case where H^+ belongs to the Higgs sector of the MSSM, we show that the leading supersymmetric radiative corrections may substantially increase the cross-section. Overall we find that the charged Higgs production process can be complementary to the neutral Higgs production processes $W\,\Phi$ and $b\,\bar{b}\,\Phi$, which have been studied under similar circumstances. Since the neutral and charged Higgs channels are enhanced in the same region of the parameter space, the simultaneous detection of all these processes could be essential for an effective experimental underpinning of the nature of these Higgs particles at the Tevatron-Run II.

[1]Updated talk presented in: *Physics at Run II Workshop on Supersymmetry/Higgs*, Fermilab, Nov. 1998, to appear in the proceedings.

1 Introduction

The top quark has been a main focus of phenomenological interest since its discovery at the Fermilab Tevatron Collider[1]. Due to its large mass it can develop large electroweak (EW) couplings with the Higgs bosons, and therefore the EW quantum corrections on physical processes involving the top quark in interplay with the Higgs sector of the model can be substantially higher than those expected from pure gauge interactions. This is indeed the case in some popular extensions of the Standard Model (SM) in which the Higgs sector is enlarged, such as the Two-Higgs-Doublet Model (2HDM) and the Minimal Supersymmetric Standard Model (MSSM)[2]. Furthermore, the reach of these quantum effects has been assessed by explicit calculations of the charged current top quark decay rates $\Gamma(t \to W^+ b)$ and $\Gamma(t \to H^+ b)$[3, 4, 5]. And its potential impact has also been demonstrated very recently for the FCNC top quark decay processes $t \to c\,\Phi$, with $\Phi = h^0, H^0, A^0$ any of the neutral Higgs bosons in the MSSM[2], by showing that the rates $\Gamma(t \to c\,\Phi)$ –most remarkably that of the lightest CP-even state h^0 – can be enhanced up to reaching detection levels in future high luminosity colliders like LHC and the LC [6].

Here we wish to point out very briefly some features that could bare relation with future Tevatron physics, namely the top quark decay into the charged Higgs, and new results on its production. The influence of the SUSY quantum effects on $t \to H^+ b$ can be so large on future (Run II) Tevatron experiments that the latter could become completely distorted if these effects are not taken into account. Moreover, the study of the corresponding effects on the cross-section for the process $p\overline{p} \to t\overline{b}\,H^-(\overline{t}b\,H^+)$ is also necessary. Especially when comparing with recent similar studies of neutral Higgs production $p\overline{p} \to b\overline{b}\,\Phi$ within the MSSM[7]. A fully-fledged analysis, however, can be quite involved as it might eventually require to compute at least the leading set of MSSM radiative corrections in all these processes, neutral and charged, in order to find out the correlation pattern among them[8]. In this way one hopes to elucidate the nature (MSSM or 2HDM) of these Higgs bosons. In this respect we recall that, in the unconstrained 2HDM case, there are also several sources of large quantum effects (see Ref.[5]), so that it is only after a combined study at the quantum level of the various Higgs channels that one may be able to shed some light on whether these bosons belong to a supersymmetric Higgs sector or not, if they are eventually discovered.

2 Top decay into charged Higgs

The decay $t \to H^+ b$ can be considered either in the context of general 2HDM's (both Type I and Type II models[2]) or in that of the MSSM (whose Higgs sector is a Type II realization). In all these cases, though for different reasons, large EW quantum effects – on top of the usual QCD corrections – can play a distinguishing role. The potential large effects stem in part from the structure of the Yukawa couplings involving top and bottom quarks:

$$\lambda_t \equiv \frac{h_t}{g} = \frac{m_t}{\sqrt{2}\,M_W\,\sin\beta} \quad , \quad \lambda_b^{\{I,II\}} \equiv \frac{h_b}{g} = \frac{m_b}{\sqrt{2}\,M_W\,\{\sin\beta, \cos\beta\}}\,, \tag{1}$$

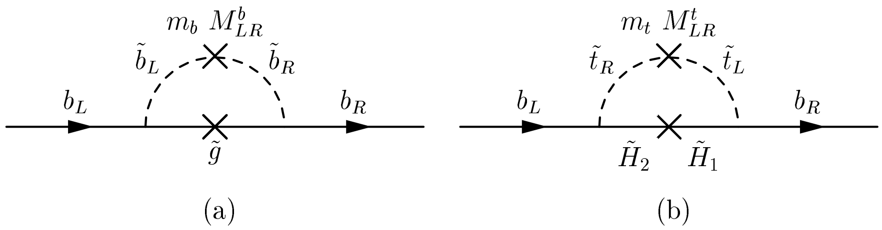


Figure 1: Feynman diagrams for the leading one loop **(a)** SUSY-QCD and **(b)** SUSY-EW contributions to the bottom quark mass in the weak eigenstate basis. The crosses represent mass insertions, and $M_{LR}^{\{t,b\}} = A_{\{t,b\}} - \mu\{\cot\beta, \tan\beta\}$.

where the value of the parameter $\tan\beta$ is a most relevant one for this kind of physics. These couplings go into the vertex Htb as follows:

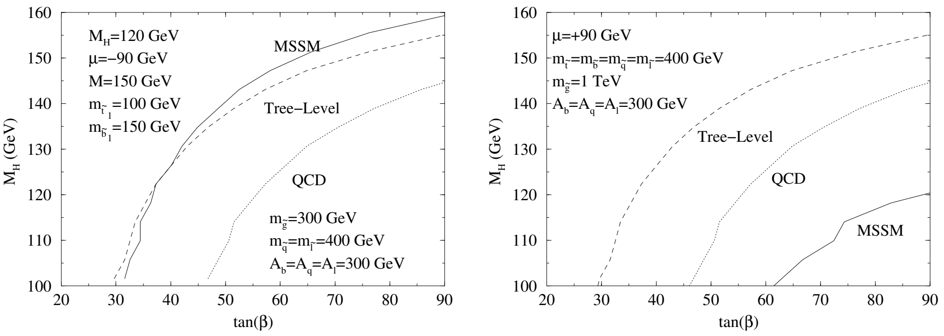
$$\mathcal{L}_{Htb} = \frac{g}{\sqrt{2}M_W}\, H^+\, \bar{t}\, [m_t \cot\beta\, P_L + m_b a_j\, P_R]\, b + \text{h.c.}\,, \tag{2}$$

where $P_{L,R} = 1/2(1 \mp \gamma_5)$ are the chiral projector operators, and $a_I = -\cot\beta$, $a_{II} = +\tan\beta$, for Type I and Type II respectively.

In the MSSM case, there are two overwhelming sources of leading quantum corrections connected with bottom mass renormalization (see below). These renormalization effects are quantitatively irrelevant in the non-SUSY 2HDM's. Alternatively, in the non-SUSY 2HDM's the loop corrections on the vertex functions can be very large [5]. For, in contrast to the MSSM case, the vertex corrections do not conspire to yield an overall negligible result because the model parameters are not constrained by the SUSY relations.

A full one-loop calculation of $\Gamma(t \to H^+ b)$ in the MSSM including all sources of large Yukawa couplings was presented in Ref.[4]. There it was shown, that the leading corrections were triggered by finite threshold contributions to the SUSY mass counterterm for the bottom quark, $\delta m_b/m_b$. These kind of effects can be both of SUSY-QCD and SUSY-EW type, and originate from diagrams like the ones in Fig. 1. In each one of them, important contributions are singled out at high $\tan\beta$ either because of the structure of the mixed squark propagator or by the direct participation of the Yukawa couplings (1). Specifically, in the SUSY-QCD case, diagram (1a) is "proportional" to the gluino mass $m_{\tilde{g}}$ times a supersymmetric D-term contributions $\mu\tan\beta$ (where μ is the Higgsino mass parameter), whereas in the SUSY-EW case, diagram (1b) goes like the SUSY-breaking trilinear A_t times the product factor $\mu\lambda_t\lambda_b^{II}$. In both cases the diagram increases as $\tan\beta$ and it would vanish in an exactly supersymmetric world.

A detailed study of the implications of the SUSY quantum effects on the Tevatron exclusion analyses of the process $t \to H^+ b$ is given in Ref.[9]. Depending on the region of the MSSM parameter space the excluded area can be much larger (see Fig.2a) or much smaller (Fig.2b) than expected in the absence of the SUSY effects, which amount to typical corrections of several ten percent in the large $\tan\beta$ region – $\tan\beta \gtrsim 30$.



(a) (b)

Figure 2: Exclusion regions at the 95% C.L. in the $\tan\beta - M_H$ plane from the $\sqrt{S} = 1.8\,TeV$ data of the Tevatron collider, using the $p\bar{p} \to t\bar{t} \to b\bar{b}\tau^\pm l^\mp \overset{(-)}{\nu}_\tau \overset{(-)}{\nu}_l$ channel. Shown are: the excluded region if the tree-level prediction for $BR(t \to H^+ b)$ is used; the excluded region when standard QCD (gluon) corrections are included; the excluded region when the total MSSM corrections are included in the prediction, for a given value of the MSSM parameters. The trilinear stop coupling A_t is fixed by the restrictions imposed by the data on $b \to s\gamma$. The two figures correspond to the scenarios with **(a)** $\mu < 0$ and **(b)** $\mu > 0$. The excluded region is the one below each curve.

3 Associated production of charged Higgs and top quark at the Tevatron

The most promising Tevatron process for charged Higgs production in association with the top quark is the following: $p\overline{p} \to t\overline{b}\,H^-(\overline{t}b\,H^+)$. This process contributes to the total cross-section for single top quark production[10], whose detailed measurement is one of the main goals at the Tevatron-Run II. On the other hand, the aforementioned charged Higgs channel is similar to the one extensively studied for the MSSM neutral Higgs bosons in Ref.[7], and they both constitute leading mechanisms for charged and neutral Higgs production at large $\tan\beta$. For charged Higgs masses below the top quark mass ($M_H < m_t$), the process $p\overline{p} \to t\overline{b}\,H^-(\overline{t}b\,H^+)$ mainly proceeds through factorization of $p\overline{p} \to t\overline{t}$ followed by the decay $t \to H^+\,b$ and/or $\overline{t} \to H^-\,\overline{b}$. The question arises now on the behavior and quantitative value of the cross-section for $M_H > m_t$, that is, when the process evolves through a three-body final state diagram in which the top quark is off-shell. The contribution from the off-shell bottom diagram is found to be negligible.

In Fig. 3 we display the cross-section[2] $\sigma(p\overline{p} \to t\overline{b}\,H^-)$ as a function of M_H within a range of charged Higgs masses covering both situations $M_H < m_t$ and $M_H > m_t$. We have fixed $\sqrt{s} = 2\,TeV$, corresponding to the Tevatron-Run II. It is seen that the three-body cross-section matches the factorized cross-section in the region $M_H < m_t$ and at the same time one sees how the cross-section extents into the domain $M_H > m_t$ where charged Higgs bosons are not produced by real top quark decays. Whereas the factorized process drops off very sharp near the phase-space end, the signal for the three-body process

[2]See Ref.[11] for more details.

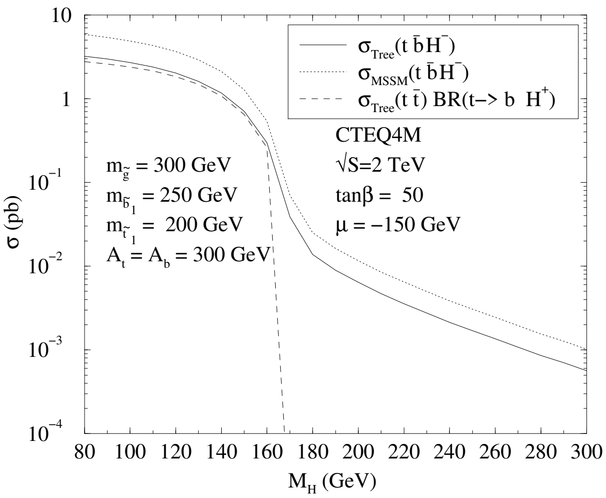


Figure 3: Total cross-section for the process $p\bar{p} \to t\bar{b}H^-$ in the MSSM for the upgraded Tevatron ($\sqrt{S} = 2\,TeV$) as a function of the charged Higgs mass. Shown are: the tree-level cross-section; the cross-section including the leading MSSM corrections; the tree-level prediction for $\sigma(p\bar{p} \to t\bar{t}) \times BR(t \to H^+ b)$ in the region where the factorization in meaningful.

remains significant and could perhaps allow to explore charged Higgs masses up to about $200 - 250\,GeV$.

In the same plot of Fig.3 we exhibit the effect of the leading SUSY corrections for a particular choice of the MSSM parameters. We emphasize that the leading effects have the same origin as explained in the previous section, i.e. they stem from the Htb vertex, whose leading contributions are depicted in Fig. 1. These effects have the remarkable property that decouple very slowly, particularly with the gluino mass[4, 8], so that for a sufficiently heavy gluino ($m_{\tilde{g}} \geq 300\,GeV$) and all squark masses above $200\,GeV$, one is guaranteed that every additional SUSY correction becomes negligible, in particular the whole plethora of SUSY-QCD effects[12] and SUSY-EW effects[13] affecting the underlying subprocess $p\overline{p} \to t\bar{t}$.

The cross-section $\sigma(p\overline{p} \to t\overline{b}\,H^-)$ can be enhanced or diminished by typical contributions that can be as large as $\pm 50\%$ for a rather heavy SUSY spectrum involving sparticle masses of a few hundred GeV – including gluino masses of order $1\,TeV$. Moreover, the largest enhancements on the cross-section $\sigma(p\overline{p} \to t\overline{b}\,H^-)$ occur in a region of parameter space which is compatible with the (indirect) restrictions ($A_t\mu < 0$) imposed by the low-energy data on $b \to s\gamma$.

Preliminary numerical results on $\sigma(p\overline{p} \to t\overline{b}\,H^-)$ were already presented in [14]. However, more recently we have checked our calculation using the COMPHEP package[15]. We have included both the gluon and quark parton distribution functions at the LO level, specifically the CTEQ4M[16] functions provided by COMPHEP. The factorization and renormalization scales were fixed at the threshold value $m_t + M_H$. These settings are similar (though not identical) to those used in Ref. [17] where no SUSY radiative effects were included. Notwithstanding, our LO cross-section (without adding SUSY effects) is significantly larger than the one provided in that reference. The largest deviation appears in the relevant region $M_H > m_t$ – by roughly a factor of $2-3$. We trace the origin of the difference to the fact that we use the bottom quark pole mass, instead of the running quark mass. In this respect, we point out that the running bottom quark mass used in that reference is unusually small. Furthermore, since the QCD effects at the NLO level are expected to be large (and positive)[18] -though they have never been explicitly computed in this particular case – we prefer not to use the effective quark masses. In general, QCD effects on cross-sections cannot be parametrized in that way.

To summarize, SUSY quantum effects on $p\overline{p} \to t\overline{b}\,H^-(\overline{t}b\,H^+)$ can be very important and should be taken into account in future analyses of charged Higgs production at the Tevatron. Most important, these effects may produce a substantial increase of the signal in regions of parameter space which are already phenomenologically favored by other experiments. A more detailed analysis of the cross-section showing the variation of the SUSY radiative corrections in different regions of the MSSM parameter space will be presented elsewhere[11].

Acknowledgments. One of the authors (JS) thanks Marcela Carena and Carlos Wagner for discussions, and the Fermilab Theory Group for hospitality and financial support. We thank A. Belyaev for his contribution in the handling of the COMPHEP package. This work has also been partially supported by CICYT under project No. AEN95-0882 and by the Deutsche Forschungsgemeinschaft.

References

[1] F. Abe *et al.* (CDF Collab.), *Phys. Rev. Lett.* **74** (1995) 2626; S. Abachi *et al.* (D0 Collab.), *Phys. Rev. Lett.* **74** (1995) 2632.

[2] J. Gunion, H.E. Haber, G.L. Kane, S. Dawson, *The Higgs Hunter's Guide* (Addison-Wesley, Menlo-Park, 1990).

[3] D. Garcia, R. A. Jiménez, J. Solà and W. Hollik, *Nucl. Phys.* **B 427** (1994) 53; A. Dabelstein, W. Hollik, C. Jünger, R. A. Jiménez and J. Solà, *Nucl. Phys.* **B 454** (1995) 75.

[4] J.A. Coarasa, D. García, J. Guasch, R.A. Jiménez, J. Solà, *Eur. Phys. J.* **C 2** (1998) 373.

[5] J.A. Coarasa, J. Guasch, W. Hollik, J. Solà, *Phys Lett.***B 442** (1998) 326.

[6] J. Guasch, J. Solà, *FCNC top quark decays in the MSSM* [hep-ph/9906268](*Nucl. Phys.* **B**, in press).

[7] M. Carena, S. Mrenna, C.E.M. Wagner, *MSSM Higgs boson phenomenology at the Tevatron collider* [hep-ph/9808312]; *ibid. The complementarity of the LEP, Tevatron and the LHC in the search for a light MSSM Higgs boson* [hep-ph/9907422].

[8] J.A. Coarasa, R.A. Jiménez, J. Solà, *Phys. Lett.* **B 389** (1996) 312; R. A. Jiménez, J. Solà, *Phys Lett.* **B 389** (1996) 53.

[9] J. Guasch, J. Solà, *Phys. Lett.* **B 416** (1998) 353.

[10] A.S. Belyaev, E.E. Boos, L.V. Dudko, *Phys. Rev.* **D 59** (1999) 075001; T. Stelzer, Z. Sullivan, S. Willenbrock, *Phys. Rev.* **D 58** (1998) 094021, and references therein.

[11] A. Belyaev, J.A. Coarasa, J. Guasch, J. Solà, preprint in preparation.

[12] Z. Sullivan, *Phys. Rev.* **D 56** (1997) 451.

[13] D. Wackeroth, in: *Quantum Effects in the MSSM*, ed. J. Solà, World Scientific 1998, p. 250 [hep-ph/9711419]; W. Hollik, W.M. Mösle, D. Wackeroth, *Nucl. Phys.* **B 516** (1998) 29.

[14] J. Solà, talk at the *Physics at Run II Workshop on Supersymmetry/Higgs*, Fermilab, Nov. 1998.

[15] E.E. Boos *et al.*, SNUTP-94-116 [hep-ph/9503280].

[16] H.L. Lai *et al.*, *Phys. Rev.* **D55** (1997) 1280

[17] F. Borzumati, talk at the *Physics at Run II Workshop on Supersymmetry/Higgs*, Fermilab, Nov. 1998; F. Borzumati, J.L. Kneur, N. Polonsky, *Higgs and slepton Strahlung at hadron colliders* [hep-ph/9905443].

[18] M. Spira, *Higgs boson production and decay at the Tevatron* [hep-ph/9810289]. Contribution to the *Physics at Run II Workshop on Supersymmetry/Higgs*, Fermilab, Nov. 1998.