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The $p\bar{p} \to tbH^{\pm}$ process at the Tevatron in HERWIG and PYTHIA simulations

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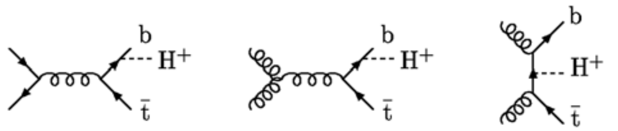
Abstract. Charged Higgs boson production in association with a top quark could be the first indication of the existence of Higgs particles. The Tevatron Run-II started data-taking in April 2001 at $\sqrt{s} = 1960$ GeV and could probe the existence of a charged Higgs boson beyond the current mass limit. We study the $p\bar{p} \to tbH^{\pm}$ production process with Monte Carlo simulations in HERWIG and PYTHIA, comparing expected cross sections and basic selection variables.

1 Introduction

Charged Higgs bosons are predicted by non-standard models, for example Two-Higgs Doublet Models such as the Minimal Supersymmetric Standard Model (MSSM). Thus, their detection and the measurement of their properties (such as the mass which is not predicted by any model) play an important rôle in the investigation of an extended Higgs sector and in the understanding of the generation of particle masses. The current limit on the charged Higgs boson mass is set by the LEP experiments at 78.6 GeV, independent of the Higgs boson decay branching fractions [1]. At the Tevatron, charged Higgs bosons could be discovered for masses well beyond this limit.

If the charged Higgs boson mass $m_{H^{\pm}}$ satisfies $m_{H^{\pm}} < m_t - m_b$, where m_t is the top quark mass and m_b the bottom quark mass, it could be produced in the decay of the top quark $t \to bH^+$. This so-called on-shell top approximation ($q\bar{q}$, $gg \to t\bar{t}$ with $t \to bH^+$) was previously used in the event generators. Throughout this paper this process is denoted by $p\bar{p} \to t\bar{t} \to tbH^{\pm}$. Owing to the large top decay width ($\Gamma_t \simeq 1.5$ GeV) and because of the additional diagrams which do not proceed via direct $t\bar{t}$ production [2,3], charged Higgs bosons could also be produced beyond the kinematic top decay threshold. The importance of these effects in the threshold region was emphasized in the previous Les Houches proceedings [4] and the calculations [2,3] are implemented in HERWIG [5,6,7] and PYTHIA [8][1]. The full process is referred to as $p\bar{p} \to tbH^{\pm}$. Examples of the graphs contributing to the $p\bar{p} \to \bar{t}bH^+$ process are [9]:



(1)

The t-channel graph is one example of a diagram which does not proceed via $t\bar{t}$ production. This graph contributes to enhanced particle production in the forward detector region.

A charged Higgs boson with $m_{H^{\pm}} < m_t$ decays predominantly into a τ lepton and a neutrino. For large values of $\tan\beta$ ($\gtrsim 5$), the ratio of the vacuum expectation values of the two Higgs doublets, this branching ratio is about 100%. The associated top quark decays predominantly into a W boson or a second charged Higgs boson, and a b-quark. The reaction

$$p\bar{p} \to tbH^{\pm} \quad (t \to bW^{\mp}) \quad (H^{\pm} \to \tau^{\pm}\nu_{\tau}) \qquad (2)$$

is a promising channel to search for the charged Higgs boson at the Tevatron. Simulations are performed at the centre-of-mass energy $\sqrt{s} = 1960$ GeV and for $\tan\beta = 20$.

2 Comparison of production cross sections

The expected production cross sections are determined using HERWIG and PYTHIA simulations, and are shown in Fig. 1. The default mass and coupling parameters of HERWIG version 6.5 and PYTHIA version 6.2 are used. The cross sections depend strongly on the top decay width over the investigated mass range. For the top width, the

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[1] HERWIG release version 6.505 and inclusion in a future official PYTHIA version.

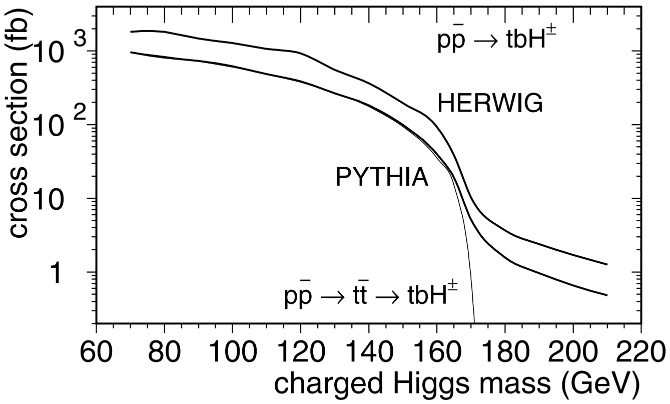

Fig. 1. Charged Higgs boson production cross section at $\sqrt{s} = 1960$ GeV for $\tan\beta = 20$. For the $p\bar{p} \to tbH^{\pm}$ process (thick lines), the HERWIG expectation is larger by about a factor 2 compared to PYTHIA because of the different default setups as described in the text. The differences between the two PYTHIA curves for the $p\bar{p} \to tbH^{\pm}$ and $p\bar{p} \to t\bar{t} \to tbH^{\pm}$ processes instead result from top decay width effects and because of the additional diagrams which do not proceed via direct $t\bar{t}$ production.

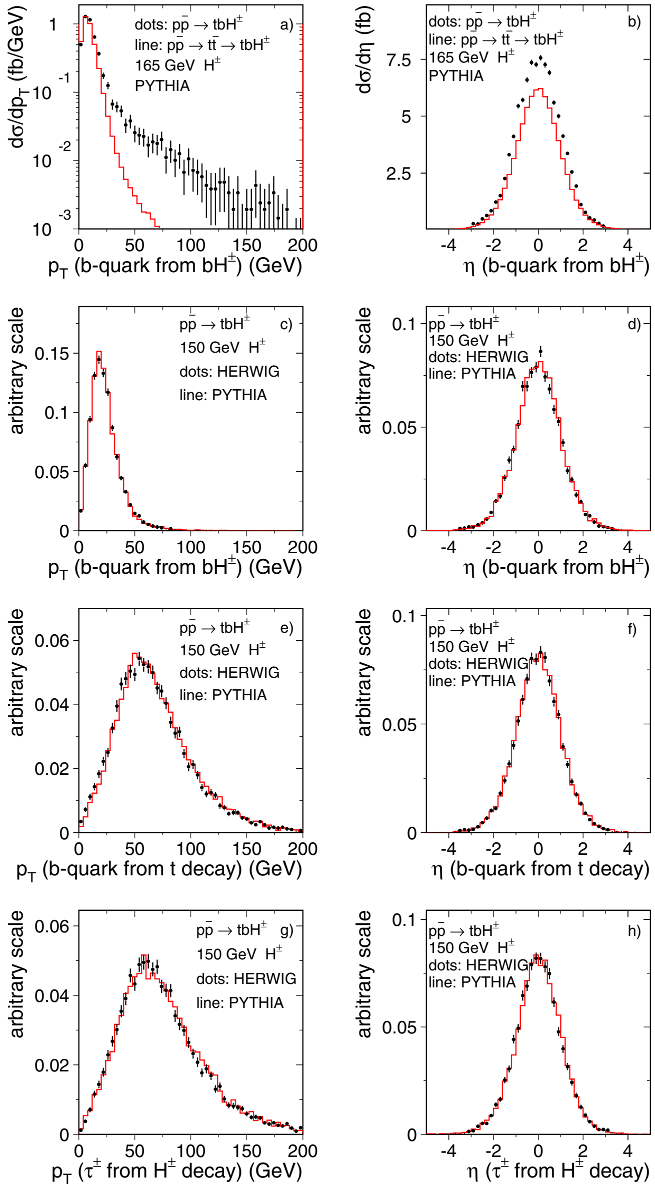

Fig. 2. Distributions of charged Higgs boson selection variables at the parton level for $\sqrt{s} = 1960$ GeV and $\tan\beta = 20$ for HERWIG and PYTHIA. The variables are described in the text. In a) and b) the differences are mainly from top off-shellness effects. In c) to h) each pair of curves is normalised to an equal area. The error bars on the dots indicate the statistical uncertainty.

Standard Model (SM) value $\Gamma_t = 1.53$ GeV is used at $m_{H^{\pm}} = 210$ GeV and the width is increased as a function of the charged Higgs boson mass to $\Gamma_t = 1.74$ GeV at $m_{H^{\pm}} = 70$ GeV in both generators. The production cross section in HERWIG is about a factor 2 larger compared to PYTHIA which can be attributed to the default choices of the standard parameters. It is mostly driven by the different choice of the heavy quark masses entering the Higgs-quark Yukawa coupling. In PYTHIA a running b-mass is used at the tbH^{+}-vertex. For $m_{H^{\pm}} = 150$ GeV the b-quark mass of 4.80 GeV is reduced to $m_b = 3.33$ GeV, while HERWIG uses $m_b = 4.95$ GeV both in the kinematics and at the vertex. Other relevant parameters are the default Parton Distribution Functions (PDFs) and the coupling constants α and α_s, as well as the scales used for evaluating the PDFs and couplings, which are not the same in the default setups of the two simulation packages.

Tests comparing the total cross sections from HERWIG and PYTHIA for *identical choices* of all above parameters were performed and confirmed that the two implementations of the hard scattering matrix elements coincide numerically. In this study, however, we maintain the default configurations of the two simulation packages. Hence, differences between HERWIG and PYTHIA in the various distributions shown in the next section may be taken as an indication of systematic errors in the event simulation.

3 Comparison of basic selection variables

At the parton level, several distributions of variables related to the event topology are compared between HERWIG and PYTHIA simulations. In addition, differences in the distributions between the $p\bar{p} \to tbH^{\pm}$ process and the $p\bar{p} \to t\bar{t} \to tbH^{\pm}$ subprocess are demonstrated. Each comparison is based on two samples of 10,000 generated events. Effects of the different event fragmentation schemes in HERWIG and PYTHIA could influence the comparison and they are not considered here. The detector simulation of the Tevatron experiments would reduce further the sensitivity of these comparisons. Figure 2 shows the transverse momentum p_T and pseudorapidity η of the following particles:

a), b) The b-quark produced in association with the $H^{\pm}$ in the $p\bar{p} \rightarrow tbH^{\pm}$ (dots) and $p\bar{p} \rightarrow t\bar{t} \rightarrow tbH^{\pm}$ (solid line) processes in PYTHIA for $m_{H^{\pm}} = 165$ GeV.
c), d) The b-quark produced in association with the $H^{\pm}$ in the $p\bar{p} \rightarrow tbH^{\pm}$ process in HERWIG (dots) and PYTHIA (solid line) for $m_{H^{\pm}} = 150$ GeV.
e), f) The b-quark from the top quark decay ($t \rightarrow bW^{\mp}$) in the $p\bar{p} \rightarrow tbH^{\pm}$ process in HERWIG (dots) and PYTHIA (solid line) for $m_{H^{\pm}} = 150$ GeV.
g), h) The τ lepton from the $H^{\pm}$ decay in the $p\bar{p} \rightarrow tbH^{\pm}$ process in HERWIG (dots) and PYTHIA (solid line) for $m_{H^{\pm}} = 150$ GeV.

The differences in the p_T and η distributions are clearly visible in Figs. 2a,b between the processes $p\bar{p} \rightarrow tbH^{\pm}$ and $p\bar{p} \rightarrow t\bar{t} \rightarrow tbH^{\pm}$. The HERWIG and PYTHIA simulations show good agreement in the kinematic distributions of Figs. 2c–h for both b-quarks and the τ lepton. The decay of the τ lepton is not considered here, but it should be noted that spin correlations must be taken into account in the study of the final state particles [9, 10].

4 Conclusions

At Tevatron Run-II, about 1000 $p\bar{p} \rightarrow tbH^{\pm}$ events per 1 fb^{-1} at $\sqrt{s} = 1960$ GeV could be produced for $m_{H^{\pm}} = 100$ GeV and $\tan\beta = 20$, while about 100 events are expected for $m_{H^{\pm}} = 150$ GeV. These expected event rates will strongly be reduced when selection criteria are applied to separate signal and background events. For the default choices of mass and coupling parameters in HERWIG and PYTHIA we observe significant differences in the simulated total cross sections. We have also studied the shape of basic selection variable distributions and found good agreement between the HERWIG and PYTHIA parton level predictions in the $p\bar{p} \rightarrow tbH^{\pm}$ process. In comparison with the $p\bar{p} \rightarrow t\bar{t} \rightarrow tbH^{\pm}$ subprocess, which was used in previous HERWIG and PYTHIA versions, for $m_{H^{\pm}} > 160$ GeV the simulation of the full process results in significantly different distributions of $tbH^{\pm}$ selection variables, mainly in the p_T distribution of the b-quark produced in association with the $H^{\pm}$.

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