PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 60, No. 2
February 2003
pp. 383–394

Working group report: Collider and B physics

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Abstract. The activities of the working group including some of the seminars are summarized. The written reports received are included.

Keywords. Higgs boson; supersymmetry; extra dimensions; B-decays.

PACS Nos 14.60.St; 14.80.Cp; 13.35.Br

Introduction

It is generally hoped that the Higgs boson, supersymmetric particles, existence of extra dimensions ..... may be discovered at the upcoming colliders. Bulk of the activities of the working group on collider and B physics revolved around these topics. Different aspects of Higgs search were discussed by A Djouadi, R M Godbole, S Moretti, D P Roy and others. From these several working group activities emerged. The reports on such activities will follow this introduction.

The search for supersymmetry at future colliders also received a lot of attention. It is believed that the stop squarks can be much lighter than other supersymmetric particles due to mixing effects and are likely to be within the reach of the upgraded Tevatron. The prospect of stop searches at the Tevatron was reviewed by M Guchait. The possible role of the hitherto neglected four-body decay of the stop was emphasized [1].

It is well-known that gauge boson fusion at high energy colliders can lead to copious production of Higgs bosons. In recent times the possibility of large scale production of SUSY particles through this mechanism has been emphasised [2]. This was reviewed by Anindya Datta. A working group activity on slepton production by this mechanism was carried out. The report by D Choudhury *et al* will follow this introduction.

K Sridhar discussed the prospective signals of extra dimensions at future colliders. Possible new decay modes of the charged Higgs particles in such models was taken up by K Agashe, D Ghosh and M Guchait. A report will follow this introduction.

Once the supersymmetric particles are discovered and their masses are measured, discovering the underlying supersymmetry breaking mechanism from the data will be a major theoretical challenge. Calculating accurately the physical masses from the soft breaking parameters of a given theory, usually specified at a high scale, is, therefore, very important. Special codes are being developed for this purpose. Discussions on some of these codes were also an important part of the WG activities.

The code SOFTSUSY (in C++) [3] for computing the sparticle spectrum with theoretical constraints on soft breaking masses provided by the users was discussed by B C Allanach. The details of this code can be found at http://allanach.home.cern.ch/allanach/softsusy.html.

A Djouadi discussed the FORTRAN code SuSpect [4] for calculating sparticle masses in the minimal supersymmetric extension of the standard model with R-parity and CP conservation as well as in models like the gravity (mSUGRA), anomaly (AMSB) and gauge (GMSB) mediated breaking models.

In order to sharpen the study of new physics signals and the associated standard model backgrounds, event generators are important tools. One such generator, the HERWIG, was discussed by S Moretti [5].

Discovery of CP violation in B-decays by the BaBar and Belle collaborations has opened up an exciting area of B-physics. In addition new decay modes of b-flavoured hardons have been observed and branching ratios of various decay modes have been measured with improved accuracy. The current experimental status of B-physics was reviewed by R Aleksan and K Abe. Lots of follow-up activities were organised. Special attention was given on the possibility of discovering new physics in B-decays.

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1. Slepton pair production from vector boson fusion

D Choudhury, Anindya Datta, D Ghosh, K Huitu, P Konar, S Moretti, and B Mukhopadhyaya

Vector boson fusion (VBF) at hadron colliders is expected to be a useful channel in looking for the Higgs boson(s) [1]. Higgs production via the VBF channel is characterised by the presence of two forward/backward jets in opposite hemispheres carrying large invariant mass and the absence of hadronic activity in the central rapidity region.

A series of recent studies [2] have also demonstrated the usefulness of this channel in exploring the chargino–neutralino sector of certain supersymmetric (SUSY) scenarios.

This is encouraging, since the detectors at the large hadron collider (LHC) will in any case look for forward/backward jet activity with high invariant mass, and any trace of new physics there will be a bonus. In this spirit, one may consider the possibility of slepton pair-production via VBF at the LHC.

Direct slepton pair production via Drell–Yan (DY) process has already been investigated in ref. [3] for the Tevatron and LHC. Corresponding cross-sections fall below the level of detectability above slepton masses of 200 GeV and 500 GeV, respectively. Ultimately, we want to investigate whether the above mass limits can be improved at the LHC by using the VBF channel for slepton pair production. (The relevance of VBF at the Tevatron is modest.) It is needless to mention that the VBF channel is suppressed by at least two powers of g_{EW} with respect to the DY channel. However, relatively large logarithms associated to the forward/backward jets in VBF may compensate the coupling reduction to some extent. Besides, for DY slepton production, cross-sections fall rather fast with the slepton mass, because of the *s*-channel structure of the process. In contrast, the t,u-channel dependence on the slepton mass in VBF is somewhat milder. Finally, the tagging of forward/backward jets in the VBF channel, together with the associated event selection criteria, helps in reducing standard model (SM) backgrounds, a handle clearly not available in the case of the DY mode.

Once produced, $\tilde{l}^+\tilde{l}^{-*}$ pairs can give rise to di-lepton signals with missing energy (along with the two forward/backward jets), via the decays $l^\pm \to l\tilde{\chi}_1^0$ (hereafter $l = e,\mu$), where $\tilde{\chi}_1^0$ is the lightest supersymmetric particle (LSP). This signature can be mimicked by leptonic decays of SM backgrounds like W^+W^- or $\tau^+\tau^-$ production and the SUSY Higgs process of H^+H^- production also via VBF [4], with the Higgs bosons both decaying into tau-neutrino pairs, followed by $\tau^\pm \to l^\pm + \not{E}_T$. The main challenge in this preliminary study is to assess whether obvious kinematic differences exist between the signal and the three mentioned backgrounds, which can help to reduce substantially the latter while maintaining the former at detectable level. A more thorough study, also including a careful scanning of the SUSY parameter space, is now in progress [8].

We have applied the following acceptance cuts:

$$\begin{aligned} &p_T(j_1,j_2) > 15\ \mathrm{GeV}, \quad 2 < |\eta(j_1,j_2)| < 5, \quad \eta(j_1)\eta(j_2) < 0, \\ &M(j_1 j_2) > 650\ \mathrm{GeV}, \quad p_T(l) > 10\ \mathrm{GeV}, \quad |\eta(l)| < 2 \end{aligned} \tag{1}$$

where the $j_{1,2}$ labels identify the two forward/backward jets.

Then, we have examined the distributions in invariant mass of the di-lepton pair as well as the missing energy spectrum for both the signal (figures 1a,b) (for some illustrative values of $M_{\tilde{l}}$ and M_{LSP}) and the three backgrounds separately (figures 1c,d). Two obvious selection criteria emerge from this simple exercise.

1. The p_T(miss) distribution is harder for the signal, with the peaks shifting to higher values for lower masses of the LSP, once the slepton mass is fixed. Hence, e.g., a p_T(miss) cut of about 50 GeV reduces the backgrounds considerably without affecting the signal in any appreciable manner.
2. The invariant mass of the di-lepton pair also has a much harder spectrum for the signal as compared to the backgrounds. Again, a cut of about, e.g., 60 GeV helps in separating the two samples.

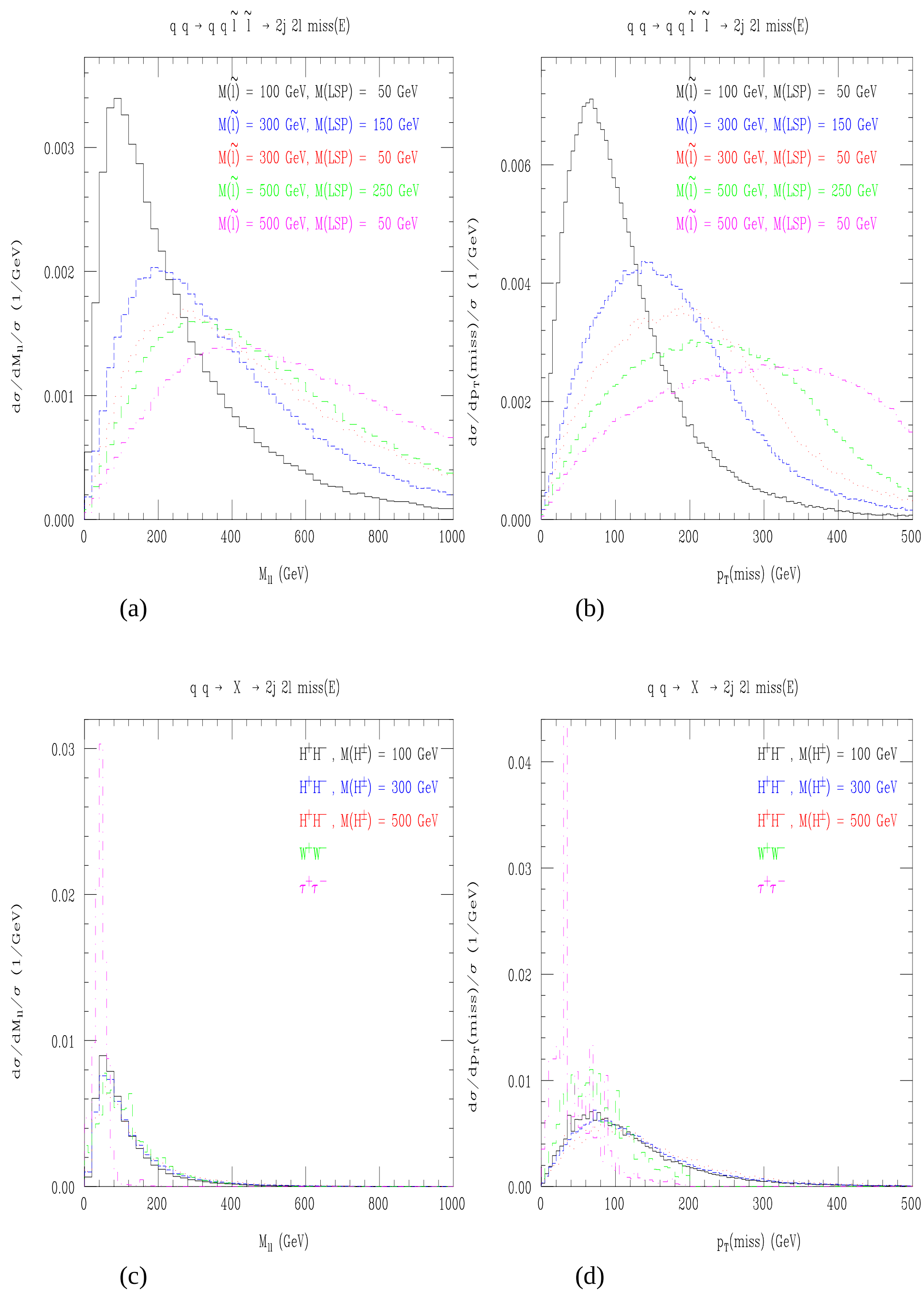

Figure 1. Invariant mass (*left*) and missing transverse momentum (*right*) distributions for the signal (*top*) and the backgrounds (*below*). Normalisations are to unity.

Table 1. Survival probability of the signal and different backgrounds after the application of the cuts.

$M_{\tilde{l}}/M_{H^\pm}$ (GeV)	M_{LSP} (GeV)	$\tilde{l}^+\tilde{l}^{-*}$ (%)	H^+H^- (%)	W^+W^- (%)	$\tau^+\tau^-$ (%)
100	50	72	67		
200	150	73	72	51	3
	50	87			
300	250	71	76		
	150	90			
	50	93			
400	350	70	79		
	250	90			
	150	94			
	50	95			
500	450	68	82		
	350	91			
	250	95			
	150	96			
	50	96			

We have made a preliminary estimate of the relative impact of the cuts on the four processes. Table 1 summarises our findings for different values of $M_{\tilde{l}}$ and M_{LSP}. Whereas the Higgs pair production background displays efficiencies similar to those of the signal (particularly for small values of the difference $M_{\tilde{l}} - M_{\mathrm{LSP}}$), the SM noises are much more strongly suppressed in comparison.

These results give us confidence for the eventual outcome of our efforts in ref. [8]. Besides, the kinematical analysis is not concluded yet and additional means of increasing the signal-to-background ratio exist, e.g., based on lepton flavour counting.

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2. Improving the LHC signature of the $H/A \to \tau^+\tau^-$ channel

S Moretti and D P Roy

The $H/A \to \tau^+\tau^-$ decay channel provides a very important channel for the MSSM Higgs search at the LHC, particularly for the large $\tan\beta$ region.

We study the possibility of improving the large hadron collider (LHC) signature of the $H/A \to \tau^+\tau^-$ channel by exploiting correlations between the τ polarisations in their 1-prong hadronic decays [1–3]. A similar method has already been proved to be useful in the case of charged Higgs bosons decaying into $\tau\nu_\tau$ pairs: see refs [4,5]. The rationale behind this is very simple and is due to the different nature of the (pseudo)scalar Higgs couplings on the one hand and the vector/axial ones of gauge bosons, on the other hand, to $\tau^+\tau^-$ pairs, appearing in signals and backgrounds, respectively. The $H/A \to \tau^+\tau^-$ decays give both right-handed or both left-handed taus, which correspond to polarisation combinations $+-$ or $-+$ (since one tau is a lepton and the other an anti-lepton). In contrast, $\gamma^*, Z \to \tau^+\tau^-$ gives left–right or right–left combinations of the tau pair, which in turn mean polarisation combinations $++$ or $--$. In top-pair production and decay, the emerging W^+W^- pair should eventually induce taus with a $--$ polarisation.

The 1-prong hadronic decays of τ's are dominated by $\tau \to \nu(\pi, \rho, a_1)$ decays. A hard τ-jet, required for τ-identification, is known to be dominated by π and longitudinal ρ, a_1 contributions for $P_\tau = +1$, while it is dominated by transverse ρ, a_1 contributions for $P_\tau = -1$ [1,2,4]. The former is characterised by an asymmetric sharing of energy between the decay pions, where the charged pion carries either very little or a very large fraction x of the τ-jet energy ($x \simeq 0$ or 1), while the latter is characterised by a symmetric sharing of energy ($x \simeq 1/2$). Thus the signals and backgrounds are expected to show distinctive correlations between the energy fractions of the two τ-jets, carried by the charged prongs. In particular, the signals are expected to show peaks at $x_1 \simeq 1, x_2 \simeq 1/2$ and $x_2 \simeq 1, x_1 \simeq 1/2$, while the backgrounds are peaked at $x_1, x_2 \simeq 1/2$ and $x_1, x_2 \simeq 1$. One can easily measure the quantities x_1, x_2 by combining the charged prong momentum measurement in the tracker with the calorimetric energy deposit of the τ-jet.

A parton level MC simulation has been done for the degenerate H/A signals at large $\tan\beta$ via $q\bar{q}, gg \to b\bar{b}H/A \to \tau^+\tau^- X$ along with the dominant $q\bar{q}, gg \to t\bar{t} \to \tau^+\tau^- X$ and $q\bar{q} \to \gamma^*, Z \to \tau^+\tau^- X$ backgrounds. The kinematical cuts are along the lines of [6] (see also [7]). The results are presented in figure 1, where the mentioned patterns are evident. (Note that no Higgs mass reconstruction has been enforced and that the signal shapes are independent of the actual value of $\tan\beta$.) One would require minimum charged prong momenta ($x_1, x_2 > 0.2$, say) for τ-identification. Then the kinematic regions can be divided into an asymmetric part (A) $x_1 > 0.8$, $0.2 < x_2 < 0.8$ and vice versa; and a symmetric part (B) $x_1, x_2 > 0.8$ and $0.2 < x_1, x_2 < 0.8$. The asymmetric region (A) is seen to favour the signals over the backgrounds. It retains 55% of each signal cross-section as against 44% and 37% of the γ^*, Z and $t\bar{t}$ background rates, respectively. This is clearly a preliminary exercise, which needs to be confirmed by more detailed analyses. The results of more sophisticated simulations, based on the HERWIG Monte–Carlo event generator [8] (now also including the $q\bar{q}, gg \to b\bar{b}H/A$ processes, see [9]) interfaced to the TAUOLA package [10] (see also [11]) for polarised τ decays and also including detector effects, will be available in the near future.

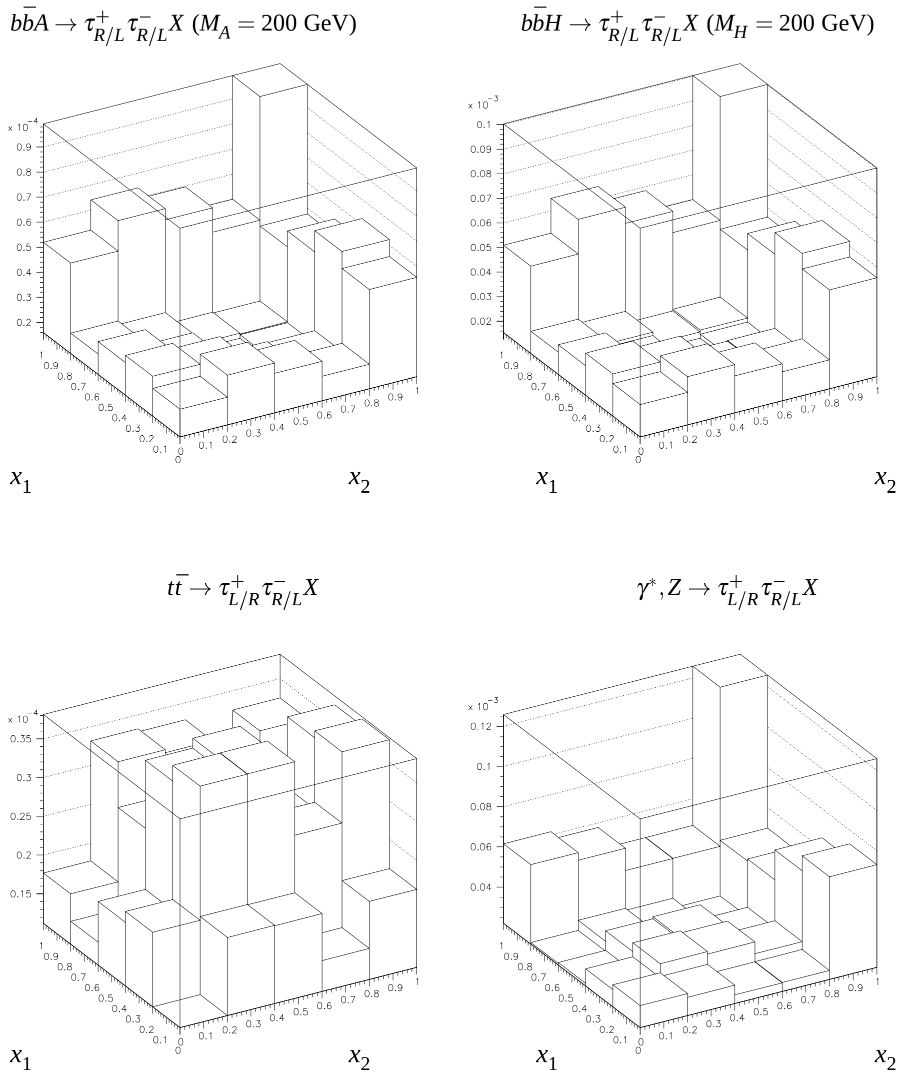

Figure 1. Doubly differential distributions in the energy fractions $x_i = p_i^{\pi^\pm}/p_i^{\tau\text{-jet}}$, where $p_i^{\pi^\pm}$ is the charged pion momentum and $p_i^{\tau\text{-jet}}$ that of the visible τ-jet, i.e, the momentum carried away by the mesons $\pi^\pm, \rho^\pm$ and $a_1^\pm$ in 1-prong decays for Higgs signals and backgrounds in the $\tau^+\tau^- X$ channel, after the following selection cuts (at parton level): $p_T(\tau\text{-jet}) > 60$ GeV, $|\eta(\tau\text{-jet})| < 2.5$, $\Delta\Phi(\tau\text{-jets}) < 175^\circ$, $\Delta R(\text{jet–jet}) > 0.4$ and $p_T(\text{miss}) > 40$ GeV. Normalisations are to the total cross-sections after cuts at $\sqrt{s} = 14$ TeV (for $M_A = M_H = 200$ GeV and $\tan\beta = 30$, in the case of the signal). Bins are 0.2 units wide.

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3. The ATLAS discovery potential of charged Higgs bosons

K A Assamagan, R M Godbole and S Moretti

This study illustrates how the ATLAS discovery potential of charged Higgs bosons in a general 2-Higgs doublet model (2HDM) through the channel $bg \to tH^-$, followed by the decays $H^- \to \tau^- \bar{\nu}_\tau$ and $t \to bjj$ (where j represents a light-flavour jet), is increased by higher order effects due to quantum chromodynamics (QCD) corrections to the production process. (See ref. [1] for some reviews of the large hadron collider (LHC) potential in the charged Higgs sector of 2HDMs.) It should in fact be recalled that this signature is currently the one with the farthest reach in the critical region $M_{H^\pm} \gtrsim m_t$ and intermediate $\tan\beta$ [2].

The mentioned corrections have been evaluated in ref. [3] for the case of ordinary QCD and confirmed by ref. [4], which also included the contributions from supersymmetric QCD. The correction is quite large, of order 30–60% or more, over the interesting region of the $(\tan\beta, M_{H^\pm})$ parameter plane. The main background to the above Higgs signature comes from double $(t\bar{t})$ and single (W^-t) top-production and decay, see ref. [2]. Until

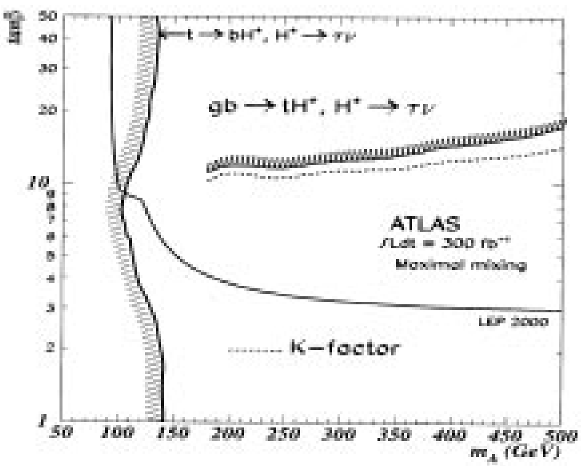

Figure 1. The ATLAS 5-σ discovery contours of 2HDM charged Higgs bosons for 300 fb^{-1} of luminosity, now including the reach in the $\tau\nu$ channel as obtained at one-loop level in QCD through overall K-factors.

now, the predictions made by ATLAS for the discovery reach in the above channels have been obtained by treating the hard scattering processes for both signal and backgrounds at lowest order only. However, one-loop QCD corrections to both $q\bar{q}, gg \to t\bar{t}$ and $bg \to tW^-$ are well known [5]. Both are found to be of similar size to those of the signal. (In fact, those for single-top coincide exactly with those for the signal in the limit $M_{H^\pm} \approx M_{W^\pm}$.) Hence, one is now justified to carry out a signal-to-background analysis at one-loop level, limitedly to the case of ordinary QCD. The way we have proceeded in doing so was simply to rescale the signal and background rates surviving the selection procedure described in [2], by the appropriate K-factors. While one may certainly devise a more sophisticated approach, taking into account that the QCD corrections may depend on the kinematics of the final state (i.e., on the selection cuts), our preliminary exercise should suffice to furnish us with a plausible indication of the prospects of $H^\pm$ discovery arising in higher order QCD [6a].

Our findings are summarised in figure 1. In the presence of QCD K-factors for both signal and backgrounds, for a given $M_{H^\pm}$, the improved reach in $\tan\beta$ of the tau–neutrino channel is clearly evident. It should also be possible, although more involved, to take further advantage of this effect also in the actual determination of $M_{H^\pm}$ and/or $\tan\beta$ via the same channel. An analysis in this respect is in now in progress [8]. The combination of these results with the improvements in other production and decay channels of $H^\pm$ bosons advocated in ref. [9] will render the charged Higgs sector of 2HDMs a privileged means of assessing the structure of such electroweak symmetry breaking (EWSB) scenarios beyond the standard model (SM).

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4. Charged Higgs decays in models with singlet neutrino in large extra dimensions

K Agashe, D Ghosh and M Guchait

Abstract. In models with singlet neutrino in large extra dimensions and with 2 Higgs doublets, the decay of charged Higgs into *left*-handed τ can be significantly enhanced, with $O(1)$ branching ratio, due to the large number of Kaluza–Klein (KK) states of the right-handed neutrino. We study the prospect of detecting these *novel* charged Higgs decays in Run II of Tevatron.

In models with large extra dimensions and TeV scale quantum gravity (ADD models) [1], small (Dirac) neutrino masses can be obtained naturally if the right-handed (RH) neutrino (denoted by ψ) propagates in the extra dimensions [2]. In these models with 2 Higgs doublets, charged Higgs has a coupling $\sim m/v$ (where m is the Dirac neutrino mass) to each KK state of RH neutrino and a charged lepton. Thus, the charged Higgs decay to (say) $\tau_{\rm L}^-$ and RH neutrino can be enhanced due to sum over the large number of KK states of RH neutrino [3]:

$$\begin{aligned}\Gamma\left(H^- \to \tau_{\rm L}\psi\right) &\sim \frac{m_{\rm H}}{8\pi}\left(\frac{m}{v}\cot\beta\right)^2 (m_{\rm H}R)^\delta \\ &\sim \frac{m_{\rm H}}{8\pi}\left(\frac{m}{v}\cot\beta\right)^2 \left(\frac{m_{\rm H}}{M_*}\right)^\delta \left(\frac{M_{\rm Pl}}{M_*}\right)^2 . \end{aligned} \quad (1)$$

Here, $m_{\rm H}$ is the charged Higgs mass, M_* is the quantum gravity scale, R is the size of the δ extra dimensions and $M_{\rm Pl}$ is the 4D Planck scale. In the second line, we have used the relation $M_{\rm Pl}^2 \sim M_*^{\delta+2} R^\delta$ of ADD models. Also, $\tan\beta$ is the ratio of VEV of Higgs doublet which couples to RH neutrino to the VEV of the other Higgs doublet.

We propose to probe these *novel* decays of H^- (recall that τ^-'s from the standard decay of charged Higgs are *right*-handed) in Run II of Tevatron. We assume that H^-, in turn, come from decays of top quarks. In 2-Higgs doublet model (2HDM) type II, $b \to s\gamma$ (which is the same as in 4D) constrains $m_{\rm H}$ to be larger than about 450 GeV and hence H^- cannot be produced in top quark decays. In 2HDM type I, where only one Higgs doublet couples to all quarks and leptons, $m_{\rm H}$ is not constrained by $b \to s\gamma$ for $\tan\beta \gtrsim 1.5$ and hence we consider this model.

Charged Higgs also decays to RH τ^- through the τ Yukawa coupling: $\Gamma\left(H^- \to \tau_{\rm R}^- \bar{\nu}\right) \sim m_{\rm H}/(8\pi)\,(m_\tau/v)^2 \cot^2\beta$. Actually, the decay width to RH τ^- is reduced compared to that in 4D 2HDM type I due to mixing between the standard model (SM) neutrino (ν) and the heavier neutrinos. Due to the same effect, the mass of the lightest neutrino is modified: $m_\nu \approx m/N$, where N is a 'normalisation factor' (for details, see [3]). Neglecting this effect, we get $\Gamma\left(H^- \to \tau_{\rm L}\psi\right)/\Gamma\left(H^- \to \tau_{\rm R}\bar{\nu}\right) \sim (m/m_\tau)^2 \left(m_{\rm H}/M_*\right)^\delta \left(M_{\rm Pl}/M_*\right)^2$. For the parameter values $m^2 \sim 10^{-2}$ (eV)^2, (as applicable to solutions to the atmospheric neutrino anomaly) $M_* \sim 2$ TeV, $\delta = 3$, and $m_{\rm H} \sim 200$ GeV, the above ratio is $\sim 3 \times 10^6$, i.e., τ's from charged Higgs decays are dominantly *left*-handed. In general, $P_\tau \equiv \left[\Gamma\left(H^- \to \tau_{\rm R}^-\right) - \Gamma\left(H^- \to \tau_{\rm L}^-\right)\right]/\left[\Gamma\left(H^- \to \tau_{\rm R}^-\right) + \Gamma\left(H^- \to \tau_{\rm L}^-\right)\right]$ can vary from -1 (for small δ and/or small M_*) to $+1$ (for large M_* and/or large δ) (see eq. (1)). Of course, $P_\tau = +1$ in 4D.

If charged Higgs is lighter than the top quark, then its only other significant decay mode is $\bar{c}s$: $\Gamma(H^- \to \bar{c}s) \sim 3\, m_{\rm H}/(8\pi)\,(m_c/v)^2 \cot^2\beta$ (which is at most comparable to $\tau_{\rm R}\bar{\nu}$). Thus, for the above values of parameters, breaking ratio (BR) for the decay mode $\tau_{\rm L}\psi$ is $O(1)$.

We consider the process $p\bar{p} \to t\bar{t}$ with $t \to bW^+$ and $\bar{t} \to \bar{b}H^-$. In ADD models, $\sigma\left(p\bar{p} \to t\bar{t}\right)$ is modified due to exchange of KK states of graviton in both the processes $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$ [4]. The modified cross-sections depend on M_* and δ. Also, BR$(t \to bH^+)$ depends on $m_{\rm H}$ and $\tan\beta$.

We reconstruct hadronic decay of W^+ and search for $H^- \to \tau^-$. Our 'signal' is *left*-handed τ^- from H^- decay.

One of the backgrounds is $t\bar{t} \to b\bar{b}W^+W^-$ with $W^- \to \tau^-$. In particular, τ^- from W^- decay is *left*-handed and so it looks like the $H^- \to \tau_{\rm L}^-$ signal. This background can be reduced by a cut on transverse mass of τ^--jet, $M_T \gtrsim M_W \sim 80$ GeV. Of course, this will dilute the $H^- \to \tau^-$ signal as well – we need a simulation to know the amount of dilution. Also, there might be other backgrounds such as fake τ's, $\tau^+\tau^-$ from Drell–Yan etc.

The cut on M_T will remove $W^- \to \tau^-$ background only if all of $E\!\!\!/_T$ comes from this W^- only. If, instead of hadronic decay of W^+, we consider $W^+ \to e^+$, μ^+ decays, then this W^+ decay will have part of the $E\!\!\!/_T$. Thus, such events cannot be used *if we wish to impose the M_T cut to reduce $W^- \to \tau^-$ background*.

In the remaining events (which will be mostly from $H^- \to \tau_{\rm L,R}^-$), the energy distribution of τ^--jets will probe τ polarisation, i.e., P_τ [5]. For example, the τ-jets are harder for $\tau_{\rm R}^-$ than for $\tau_{\rm L}^-$. Again, we need a simulation to determine how sensitive this distribution is to $x_{\rm LR}$, especially in view of the possibly limited statistics due to all the cuts. *These simulations are in progress*. Evidence for P_τ close to -1 (even, say, $P_\tau < 0$, basically different from $+1$) will be a smoking gun signal for this model.

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