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Working group report: Collider Physics

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Abstract. This is summary of the activities of the working group on collider physics in the IXth Workshop on High Energy Physics Phenomenology (WHEPP-9) held at the Institute of Physics, Bhubaneswar, India in January 2006. Some of the work subsequently done on these problems by the subgroups formed during the workshop is included in this report.

Keywords. Colliders; new physics; supersymmetry; CP-violation.

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The working group on collider physics (Working Group I) was constituted in order to focus on some interesting and technically viable projects in the area, which is of immense interest in view of (a) the imminent commissioning of the large hadron collider (LHC) at CERN, and (b) the growing probability that it will be followed by an international linear collider (ILC) about 6–7 years later. In view of the requirements of the hour and the available skills and interests, it was decided to focus on searches for physics beyond the Standard Model. The problems identified and discussed, together with follow-up work, are summarized in this report. The working group activity consisted of two parts, viz., (A) focussed presentations by working group members on topics of relevance and (B) discussions and working sessions on possible research problems.

(A) Presentations

There were three presentations by members of the working group on topics of relevance to the other discussions. These were by (1) Gobinda Majumdar on *Issues in the construction of detectors for the ILC*, (2) Satyaki Bhattacharyya on *Photon detection efficiency in the measurement of* $H^0 \to \gamma\gamma$, and (3) Ben Allanach on *Dark matter constraints on the parameter space of the MSSM and mSUGRA*.

1. *Issues in the construction of detectors for the ILC*

Gobinda Majumdar

A summary of the presentation is given below.

The main motivation of the ILC detector is precision physics. However, the kind of precision physics depends on the discovery of new particles/effects in the LHC experiments. The range of the center of mass energy varies from Z-pole to 1 TeV. These constraints force the experimental community to design and build detector(s) where performances of each sub-detector is much better than the best sub-detector earlier used in a HEP experiment. For example:

(1) Central tracking chamber (CTC) requires momentum resolution, $\sigma_{1/p} \sim 5 \times 10^{-5}$, which is 10 (3) times better than the LEP (CMS) experiment, in order to measure the Higgs boson mass in Higgstrahlung processes through Z-mass reconstruction from charged leptons.

(2) Impact parameter resolution $\sigma_{d0} < 5\ \mu\text{m} \oplus 10\ \mu\text{m}/P$ (GeV) of the vertex detector, which is three times better than the best vertex detector used in the SLD, is required to establish Higgs coupling to fermions (separation between b, c jets from u, d, s jets).

(3) Hadronic jet energy resolution in calorimeter, $\sigma_E/E \sim 0.3/\sqrt{E}$ (GeV) which is half of the best calorimeter used in ZEUS experiment. This is required to distinguish $e^+e^- \to \nu_e\bar{\nu}_e W^+W^-$ and $e^+e^- \to \nu_e\bar{\nu}_e ZZ$ as well as any physics process requiring distinction in jets from Z and W decays.

Eventually, of course, detector R&D will dictate the final detector design.

At present, there are four different detector groups working independently to design the ILC detector. The first three are (i) global linear detector (based on

JLC study), (ii) large detector concept (based on TESLA) and (iii) silicon detector (mainly by American group). A new design of ILC detector based on the concept of compensating calorimeter is also under consideration, which is known as the fourth concept. For the vertex detector, until now, we do not have detectors which can give vertex resolution, σ_{d0} better than 5 μm $\oplus$ 10 μm/P (GeV), but dozens of technologies are under study to achieve this goal, e.g., CAP, CPCCD, DEPFET etc. For the central tracking chamber, new gas detector technologies, (i) gas electron multiplier (GEM) and (ii) MICRO MEsh GAseous Structure (MICROMEGAS) have shown the required performance levels. On the calorimeter side, it is difficult to achieve the required resolution only by improving hardware. Thus, studies are going on in parallel to improve it through software as well. Instead of using the conventional jet clustering algorithm, 'particle flow algorithm' is more promising, but it requires a high granularity detector. The recent development of a multi-pixel photon counter (MPPC), which has very large quantum efficiency to convert photons to electrons and also has a very large internal gain is a boost for this programme. Scintillator-based hadron calorimeters with MPPC readout system can achieve a resolution of $\sigma_E/E \sim 0.3/\sqrt{E}$ (GeV). In the other direction, dual/triple readout module (DREAM/TREAM) in the fourth concept shows that they can go beyond this precision.

To summarize, detector R&D is going full steam ahead to achieve the desired level of precision.

2. *Dark matter constraints on the parameter space of the MSSM and mSUGRA*

Ben Allanach

A summary of the presentation is given below.

In the R-parity conserving MSSM, the stable neutralino $\tilde{\chi}_1^0$ is a good cold dark matter (CDM) candidate. Calculation of the neutralino relic density must take into account annihilation in the early Universe into ordinary matter, through processes such as $\tilde{\chi}_1^0 + \tilde{\chi}_1^0 \rightarrow p + p'$. Current fits to the WMAP data require the Universe to have about 23% of CDM, corresponding to a dark matter density $0.094 < \Omega_{\rm DM}h^2 < 0.129$ at 2σ. Based on the cross-section $\sigma(\tilde{\chi}_1^0 + \tilde{\chi}_1^0 \rightarrow p + p')$, the SUSY prediction of CDM is generated using the software microMEGAS to solve coupled Boltzmann equations, with the spectrum generated using the package SoftSUSY. It is implicitly assumed that neutralinos constitute all the CDM.

The overlap of the above with collider physics arises from the fact that we can, in principle, hope to measure $\sigma(p + p \rightarrow \tilde{\chi}_1^0 + \tilde{\chi}_1^0)$ directly in collider experiments, especially in the LHC. Conversely, the requirement that $\sigma(\tilde{\chi}_1^0 + \tilde{\chi}_1^0 \rightarrow p + p')$ be at just the level which produces the required amount of CDM, imposes severe constraints on the SUSY parameter space. These were discussed in the context of the MSSM constrained by mSUGRA, in different scenarios for the SUSY-breaking parameters. Uncertainties in the measurements and hence constraints were focussed upon. However, there has been no discussion of direct measurement of $\sigma(p + p \rightarrow \tilde{\chi}_1^0 + \tilde{\chi}_1^0)$.

(B) Research problems

The research problems identified and discussed are listed below.

1. *Z-boson decay to a graviton and a photon*

B Allanach, A Datta, S K Rai, S Raychaudhuri and K Sridhar

The collider phenomenology of massive Kaluza–Klein modes of a graviton propagating in more than four canonical dimensions has been an important topic of discussion in the literature since 1998 [1]. While most of the tree-level processes in the basic ADD and RS models have been calculated and are now being included in event generators, processes at the one-loop level involving gravitons have received very little attention. One of the most interesting of these is the process $Z^0 \to \gamma + G_n$, where G_n denotes the nth Kaluza–Klein mode of the graviton field. Typical Feynman diagrams for this process are shown in figure 1. The subgroup identified the computation of this decay width as a project which was initiated during the workshop.

When compared with similar processes such as $Z^0 \to \gamma + H^0$, the process $Z^0 \to \gamma + G_n$ has the following novel features:

- All (charged) fermions in the loops contribute equally, except for a factor related to their electric charge.
- There is an incoherent sum over final state G_n's in the case of ADD-type scenarios, where the observable signal is $Z^0 \to \gamma + \not{E}_{\rm T}$.

A computation of the process $Z^0 \to \gamma + G$ in linearized Einstein gravity in four dimensions is already available [2], which establishes the gauge cancellations as expected and evaluates the form factors for the amplitude approximately. A similar calculation is under way, where (a) the massless graviton field G_n is replaced by a massive Kaluza–Klein mode G_n and (b) the loop integrals are computed in closed form, which is possible in the limit of equal internal masses and one massless external leg. On rough estimates, it is expected that when the calculation is completed, Z-peak data from LEP-1 will provide competitive bounds on the parameters of the ADD model with large extra dimensions.

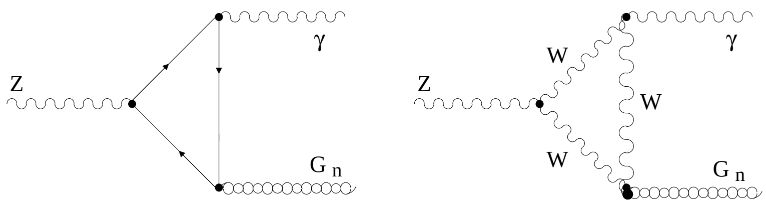

Figure 1. Typical Feynman diagrams giving rise to the process $Z^0 \to \gamma + G_n$ at one loop. The solid lines in the diagram on the left represent any charged fermion of the Standard Model.

In the Randall–Sundrum model, the current bounds of a few hundred GeV on the mass of the lightest graviton mode render the process $Z^0 \to \gamma + G_n$ kinematically disallowed. However, we can simply use crossing symmetry to calculate the width of $G_n \to \gamma + Z^0$, which process can then be used to study graviton resonances in pp collisions at the LHC. It is possible that the decay $Z^0 \to \ell^+\ell^-$ will provide clean final states and hence a better discrimination of graviton signals as compared to other, more standard modes.

The actual computation, which is long and somewhat tedious, is currently under way and is expected to be completed soon. The subgroup hopes to report this in a forthcoming publication.

2. *SUSY studies at the LHC in the light of dark matter constraints*

B Allanach, S P Das, R M Godbole, M Guchait, S Kraml and D P Roy

Taking into account dark matter constraints, we find that in SUSY scenarios with stau co-annihilation, the mass difference between the lighter stau and the (neutralino) LSP is 10 GeV or even smaller. In such a scenario, the stau decay $\tilde{\tau}_{\rm R}^{\pm} \to \tau^{\pm} + \tilde{\chi}_1^0$ will produce a soft τ lepton which may or may not be detected at the LHC. These τ lepton will be produced in cascade decays of the form given in figure 2.

As a preliminary study, the SPS3 values were chosen, viz., $m_0 = 80$ GeV, $m_{1/2} = 400$ GeV, $A_0 = 0$, $\tan\beta = 10$, sgn $\mu = +$. In this scenario, the low-lying sparticle behaviour was determined as shown in table 1. This was not, perhaps, the most favourable point in the parameter space, but it was a reasonable point to start from.

The cascade decays as shown in figure 2 were generated and the transverse momentum distributions of the two τ leptons are shown in figure 3.

There should be no problem in detection of the taus from neutralino decay, since the average $p_{\rm T}$ is 147 GeV. On the other hand, the figure makes it clear that $p_{\rm T}$ of taus from stau decay is small. In fact, the average comes out as about 19 GeV, making it difficult to detect these soft tau jets above the QCD background. It is very unlikely, therefore, that we will be able to get a $m_{\tau\tau}$ end-point.

Similar results were obtained for τ's from chargino decay, with the mean $p_{\rm T}$ as 26 GeV. However, the rapidity distribution lies within the range of the tracker and so there is more hope in this case.

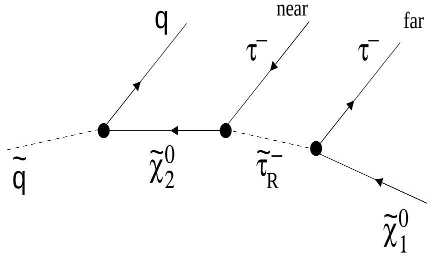

Figure 2. Cascade decay of a squark with an intermediate stau state.

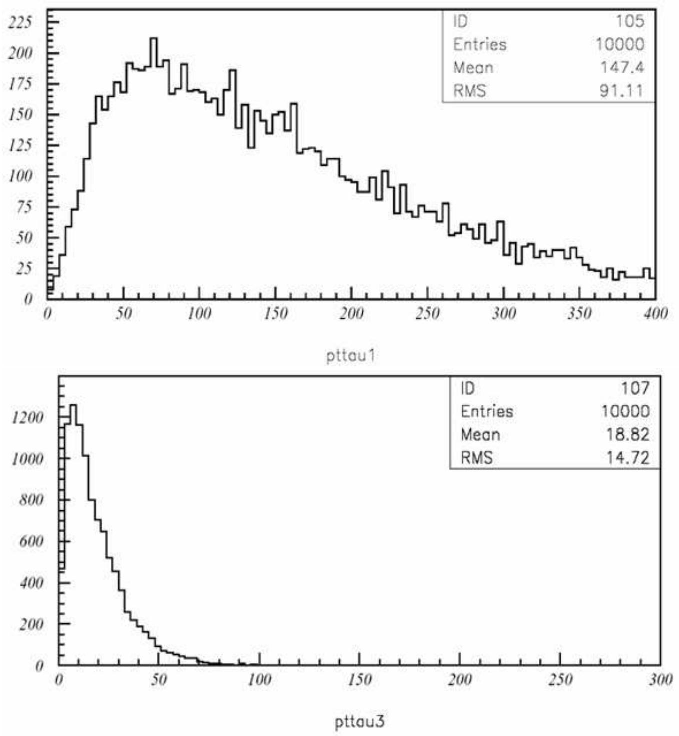

Figure 3. Transverse momenta of τ leptons arising in decays of the second neutralino state at the LHC. Top: τ's arising from neutralino decay, and Bottom: τ's arising from stau decay.

Table 1. Light sparticles with the SPS3 parameters.

Particle	Mass (GeV)	Decays
$\tilde{\chi}_1^0$	158	Stable
$\tilde{\tau}_1$	168	100% to tau + LSP
$\tilde{\nu}_\tau$	275	87% to neutrino + LSP
		12% to W + stau
$\tilde{\chi}_2^0$	304	16% to stau + tau
		16% to slepton + lepton
$\tilde{\chi}_1^\pm$	304	19% to stau + neutrino
		20% to sneutrino + tau

Further studies are in progress, including a scan of the parameter space to see if a more favourable spectrum can be obtained.

3. *Moderately light charged Higgs boson in NMSSM and CPV-MSSM*

D P Roy and R M Godbole

Introduction: In this note we discuss some aspects of the phenomenology of a light charged Higgs ($M_{\mathrm{H}^+} \lesssim 150$ GeV), allowed at low and moderate values of $\tan\beta$, in the NMSSM and CPV-MSSM, respecting all the LEP-II bounds. In NMSSM with the $H^\pm$ near its lower mass limit ($M_{\mathrm{H}^+} \simeq 120$ GeV), and a light pseudoscalar ($M_{A_1^0} \simeq 50$ GeV) with a very significant doublet component, the charged Higgs boson is expected to decay dominantly via the standard $H^+ \to \tau^+\nu$ mode. One can probe this mass range via the $t \to bH^+ \to b\tau^+\nu$ channel at Tevatron and especially at LHC. For somewhat heavier charged Higgs boson ($M_{\mathrm{H}^\pm} > 130$ GeV) the dominant decay via the $H^+ \to W^+\ A_1^0$ channel provides a probe for not only a light H^+ but also a light A_1^0 [3] in the moderate $\tan\beta$ region, where its dominant decay mode is into a $b\bar{b}$ final state. Similar situation also attains in the CP-violating MSSM as well. The CP-violating MSSM allows existence of a light neutral Higgs boson ($M_{\mathrm{H}_1} \lesssim 50$ GeV) in the CPX scenario in the low $\tan\beta (\lesssim 5)$ region, which could have escaped the LEP searches due to a strongly suppressed H_1ZZ coupling. The light charged H^+ decays dominantly into the WH_1 channel again giving rise to a striking $t\bar{t}$ signal at the LHC, where one of the top quarks decays into the $bb\bar{b}W$ channel, via $t \to bH^\pm, H^\pm \to WH_1$ and $H_1 \to b\bar{b}$. The characteristic correlation between the $b\bar{b}$, $b\bar{b}W$ and $bb\bar{b}W$ invariant mass peaks helps reduce the SM background drastically.

Moderately light $H^\pm$ in NMSSM: As discussed above, the solution of the so-called μ-problem of the MSSM was the original motivation for the NMSSM. The effect of the additional complex singlet scalar S in the NMSSM on the charged Higgs phenomenology mainly comes through a relaxation of the mass limits of A^0 and H^+ in the MSSM. This arises from the modification of the MSSM mass relations between the doublet scalars $H_{1,2}$ and pseudoscalar A and the resulting modification of the H_1 mass bound. The masses of the $A_i^0, i = 1, 2$ and $H_i, i = 1, 3$ can be written in terms of the various parameters of the NMSSM: the dimensionless parameters λ, κ appearing in the superpotential, as well as the corresponding soft trilinear terms A_λ, A_κ and the vacuum expectation value of the singlet scalar field $\langle S\rangle = x = v_S/\sqrt{2}$. In particular, the resulting upper bound of the lightest Higgs scalar mass including the radiative correction ϵ, is [4–9]

$$M_{\mathrm{H}_1}^2 \leq M_Z^2 \cos^2(2\beta) + \frac{2\lambda^2 M_W^2}{g^2} \sin^2(2\beta) + \epsilon, \tag{1}$$

where contribution specific to the NMSSM in addition to the terms in MSSM is given by the middle term. This is most pronounced in the low-to-moderate $\tan\beta$ region, where the MSSM mass bound coming from the first term of eq. (1) is very small. Therefore it relaxes the MSSM bound on M_{H_1} and the resulting lower limit of M_{A_i}, most significantly over this range of $\tan\beta$. This in turn relaxes the lower limit of the charged Higgs mass, which is related to the doublet pseudoscalar mass via

$$M_{\mathrm{H}^+}^2 = M_A^2 + M_W^2 \left(1 - \frac{2\lambda^2}{g^2}\right) \tag{2}$$

along with a small radiative correction. This is helped further due to the additional (negative) contribution in eq. (2). Note that the additional contributions of eqs (1) and (2) depend only on the $\hat{S}\hat{H}_u\hat{H}_d$ coupling λ, in the superpotential of eq. (4.7). Therefore, eqs (1) and (2) hold also for the minimal nonminimal supersymmetric Standard Model (MNSSM), which assumes only this term in the superpotential [10–12]. Finally the upper bound of eq. (1) will only be useful if one can find an upper limit on λ. Such a limit can be derived [4–6] from the requirement that all the couplings of the model remain perturbative up to some high energy scale, usually taken to be the GUT scale. Such an upper limit on λ has been estimated in [13] as a function of $\tan\beta$ using two-loop renormalization group equations.

For quantitative evaluation of the NMSSM Higgs spectrum we consider the complete Higgs potential as given in terms of these parameters in [14]. The lower limit of the $H^{\pm}$ mass has been estimated as a function of $\tan\beta$ in [13] by varying all these five NMSSM parameters over the allowed ranges, which include the constraints from LEP-2. The resulting $H^{\pm}$ mass limit is shown in figure 4 along with the most conservative MSSM limit, corresponding to maximal stop mixing, which gives the largest radiative correction ϵ. The NMSSM limit has practically no sensitivity to stop mixing. The LEP-2 mass limit from direct search of $H^+ \to \tau^+\nu$ events is also shown for comparison [15]. There is no limit from Tevatron in the moderate $\tan\beta$ region shown in figure 4.

One sees from figure 4 that even the most conservative MSSM limit implies $H^{\pm}$ mass ≥ 150 GeV (175 GeV) for $\tan\beta \leq 6$ (4). In contrast, in the NMSSM one can have a $H^{\pm}$ mass $\lesssim 120$ GeV over this moderate $\tan\beta$ region, going down to the direct LEP-2 limit of 86 GeV at $\tan\beta \simeq 2$. Note however that requiring the effective

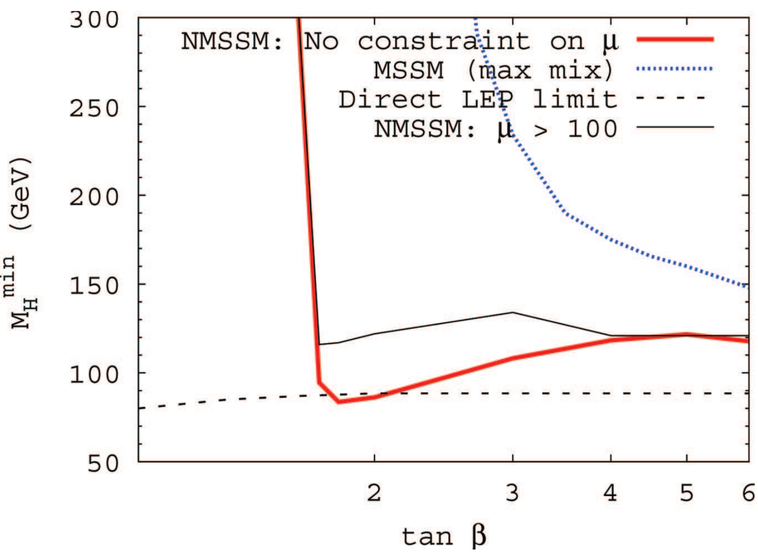

Figure 4. The indirect lower bounds on the charged Higgs boson mass following from the LEP limits on the neutral Higgs bosons in the MSSM (maximal stop mixing) and the NMSSM. The direct LEP limit on the charged Higgs boson mass is also shown for comparison.

Table 2. Examples of dominant $H^{\pm} \rightarrow WA_1^0$ decay in the NMSSM. These decay branching fractions are shown along with the Higgs boson masses and the other model parameters.

$\tan\beta$	M_{H^+} (GeV)	M_{A_1} (GeV)	B_{A_1} (%)	λ, κ	$x = v_s/\sqrt{2}, A_\lambda, A_\kappa$ (GeV)
2	147	38	94	0.45, −0.69	224, −8, 2
3	159	65	83	0.33, −0.70	305, 40, 38
4	145	48	89	0.28, −0.70	563, 170, 85
5	150	10	91	0.26, −0.54	503, 109, 38

μ parameter $\mu_{\text{eff}} = \langle S \rangle \lambda$ be greater than 100 GeV, as favored by the LEP chargino search, increases this mass limit to $\gtrsim 120$ GeV [11]. The steep vertical rise at left reflects the well-known fixed-point solution at $\tan\beta = 1.55$, where the top Yukawa coupling blows up at the GUT scale. Thus, allowing for possible intermediate scale physics one can evade the steep NMSSM mass limit at low $\tan\beta$ [16]. In contrast, the MSSM limit holds independent of any intermediate scale physics ansatz.

We have investigated the neutral scalar and pseudoscalar Higgs spectrum of the NMSSM, when $H^{\pm}$ lies near its lower mass limit ($M_{\mathrm{H}^+} \simeq 120$ GeV). The lightest scalar is dominantly singlet ($M_{\mathrm{H}_1} \simeq 100$ GeV) while the doublet scalars are relatively heavy ($M_{\mathrm{H}_{2,3}} > 120$ GeV). On the other hand, there is often a light pseudoscalar ($M_{A_1^0} \simeq 50$ GeV) with a very significant doublet component. Consequently a light charged Higgs boson of mass $\simeq 120$ GeV is expected to decay dominantly via the standard $H^+ \rightarrow \tau^+\nu$ mode. Thus one can probe this mass range via the $t \rightarrow bH^+ \rightarrow b\tau^+\nu$ channel at Tevatron and especially at LHC. On the other hand, a somewhat heavier charged Higgs boson ($M_{\mathrm{H}^\pm} > 130$ GeV) can dominantly decay via the $H^+ \rightarrow W^+A_1^0$ channel [3]. In fact this seems to be a very favorable channel to probe for not only H^+ but also a light A^0 in the moderate $\tan\beta$ region, where A^0 is expected to decay mainly into the $b\bar{b}$ or $\tau^+\tau^-$ mode. Table 2 shows some illustrative samples of NMSSM Higgs spectra where H^+ decays dominantly into the $W^+A_1^0$ mode. These results are obtained by scanning the NMSSM parameter space. Note that in each case the effective μ parameter $\mu_{\text{eff}} = \lambda\langle S \rangle$ is greater than 100 GeV as favored by the LEP chargino limit. The decay branching fractions are shown along with the Higgs boson masses and the other model parameters.

Light $H^{\pm}$ in CP-violating MSSM: Interestingly one can have a similar signal in the CP-violating MSSM due to large scalar–pseudoscalar mixing. The CP-violating MSSM allows existence of a light neutral Higgs boson ($M_{\mathrm{H}_1} \lesssim 50$ GeV) in the CPX scenario in the low $\tan\beta(\lesssim 5)$ region, which could have escaped the LEP searches due to a strongly suppressed H_1ZZ coupling. The light charged H^+ decays dominantly into the WH_1 channel giving rise to a striking $t\bar{t}$ signal at the LHC, where one of the top quarks decays into the $bb\bar{b}W$ channel, via $t \rightarrow bH^{\pm}, H^{\pm} \rightarrow WH_1$ and $H_1 \rightarrow b\bar{b}$. The characteristic correlation between the $b\bar{b}$, $b\bar{b}W$ and $bb\bar{b}W$ invariant mass peaks helps reduce the SM background, drastically [17]. Note that this signal is identical to the NMSSM case discussed above.

Table 3. Range of values for BR($H^+ \to H_1 W^+$) and BR($t \to bH^+$) for different values of $\tan\beta$ corresponding to the LEP allowed window in the CPX scenario, for the common phase $\Phi_{\rm CP} = 90°$, along with the corresponding range for the H_1 and H^+ masses. The quantities in the bracket in each column give the values at the edge of the kinematic region where the decay $H^+ \to H_1 W^+$ is allowed.

$\tan\beta$	3.6	4	4.6	5
BR($H^+ \to H_1 W^+$) (%)	>90(87.45)	>90(57.65)	>90(50.95)	>90(46.57)
BR($t \to bH^+$) (%)	∼0.7	0.7–1.1	0.9–1.3	1.0–1.3
$M_{\rm H^+}$ (GeV)	<148.5(149.9)	<139(145.8)	<130.1(137.5)	<126.2(134)
$M_{\rm H_1}$ (GeV)	<60.62(63.56)	<49.51(65.4)	<36.62(57.01)	<29.78(53.49)

As already mentioned, a combined analysis of all the LEP results shows that a light neutral Higgs is still allowed in the CPX [18] scenario in the CPV-MSSM. The experiments provide exclusion regions in the $M_{\rm H_1}$–$\tan\beta$ plane for different values of the CP-violating phases, for the following values of the parameters:

$$\text{Arg}\, A_t = \text{Arg}\, A_b = \text{Arg}\, M_{\tilde{g}} = \Phi_{\rm CP}, \tag{3}$$

$$M_{\rm SUSY} = 0.5\ \text{TeV}, \quad M_{\tilde{g}} = 1\ \text{TeV}, \tag{4}$$

$$M_{\tilde{B}} = M_{\tilde{W}} = 0.2\ \text{TeV}, \tag{5}$$

$$\Phi_{\rm CP} = 0°, 30°, 60°, 90°. \tag{6}$$

Combining the results of Higgs searches from ALEPH, DELPHI, L3 and OPAL, the authors in ref. [19] have also provided exclusion regions in the $M_{\rm H_1}$–$\tan\beta$ plane as well as $M_{\rm H^+}$–$\tan\beta$ plane for the same set of parameters. While the exact exclusion regions differ somewhat in the three analyses [19,20] they all show that for phases $\Phi_{\rm CP} = 90°$ and 60° LEP cannot exclude the presence of a light Higgs boson at low $\tan\beta$, mainly because of the suppressed $H_1 ZZ$ coupling. The analyses of ref. [19] further shows that in the same region the $H_1 t\bar{t}$ coupling is suppressed as well. Thus this particular region in the parameter space cannot be probed either at the Tevatron where the associated production W/ZH_1 mode is the most promising one or at the LHC as the reduced $t\bar{t}H_1$ coupling suppresses the inclusive production mode and the associated production modes W/ZH_1 and $t\bar{t}H_1$, are suppressed as well. This region of ref. [19] corresponds to $\tan\beta \sim 3.5$–5, $M_{\rm H^+} \sim 125$–140 GeV, $M_{H_1} \lesssim 50$ GeV and $\tan\beta \sim 2$–3, $M_{H^+} \sim 105$–130 GeV, $M_{\rm H_1} \lesssim 40$ GeV, for $\Phi_{\rm CP} = 90°$ and 60° respectively. In the same region of the parameter space where $H_1 ZZ$ coupling is suppressed, the $H^+ W^- H_1$ coupling is enhanced because these two sets of couplings satisfy a sum-rule. Further, in the MSSM a light pseudoscalar implies a light charged Higgs, lighter than the top quark.

Table 3 shows the behaviour of the $M_{\rm H^+}$, $M_{\rm H_1}$ and the BR($H^+ \to H_1 W^+$), for values of $\tan\beta$ corresponding to the above mentioned window in the $\tan\beta$–$M_{\rm H_1}$ plane, of ref. [19]. It is to be noted here that indeed $H^\pm$ is light (lighter than the top) over the entire range, making its production in t decay possible. Further,

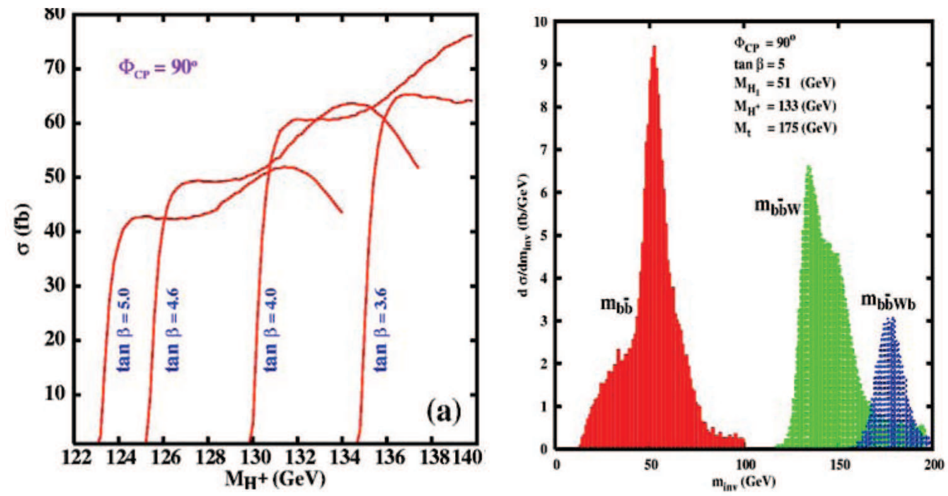

Figure 5. Variation of the cross-section with $M_{\rm H^+}$ for four values of $\tan\beta = 3.6, 4, 4.6$ and 5 is shown in the left panel, for the CP-violating phase $\Phi_{\rm CP} = 90°$. These numbers should be multiplied by ∼0.5 to get the signal cross-section to take into account the b-tagging efficiency. The right panel shows the $m_{b\bar{b}}, m_{b\bar{b}W}$ and the $m_{b\bar{b}Wb} = M_{\rm t}$ invariant mass distributions, for this choice of CP-violating phase and $\tan\beta = 5, M_{\rm H^+} = 133$ GeV, corresponding to a light neutral Higgs H_1 with mass $M_{\rm H_1} = 51$ GeV $M_{\rm t}, M_W$ mass window cuts have been applied [17].

$H^\pm$ decays dominantly into H_1W, with a branching ratio larger than 47% over the entire range where the decay is kinematically allowed, which covers practically the entire parameter range of interest, viz. $M_{\rm H_1} < 50$ GeV for $\Phi_{\rm CP} = 90°$. It can also be seen from the table that BR$(H^\pm \to H_1W)$ is larger than 90% over most of the parameter space of interest. So not only that H^+ can be produced abundantly in the t decay giving rise to a possible production channel of H_1 through the decay $H^\pm \to H_1W^\pm$, but also this decay mode will be the only decay channel to see this light $(M_{\rm H^\pm} < M_t)$ $H^\pm$. The traditional decay mode of $H^\pm \to \tau\nu$ is suppressed by over an order of magnitude and thus will no longer be viable. Thus the process

$$p\bar{p} \to t(bH^+ \to bW^+H_1)\bar{t}(bW^- \to bl\nu_l/q\bar{q}'),$$

with H_1 further decaying into a $b\bar{b}$ pair and W^+ decaying into a $l\nu_l(q\bar{q}')$ pair will allow a probe of both the light H_1 and a light $H^\pm$ in this parameter window in the CP-violating MSSM in the CPX scenario.

As can be seen from figure 5 the largest signal cross-section case is ∼38 fb and the signal cross-section is $\gtrsim$20 fb for $M_{\rm H_1} \gtrsim 15$ GeV. It is clear from the right panel of figure 5, that there is simultaneous clustering in the $m_{b\bar{b}}$ distribution around $\simeq M_{\rm H_1}$ and in the $m_{b\bar{b}W}$ distribution around $M_{\rm H^\pm}$. This clustering feature can be used to distinguish the signal over the Standard Model background. As a matter of fact the estimated background to the signal coming from the QCD production of $t\bar{t}b\bar{b}$ once all the cuts (including the mass window cuts) are applied, to the signal type events is less than 0.5 fb, in spite of a starting cross-section of 8.5 pb. The major reduction is brought about by requiring that the invariant mass of $bbbW$ be within 25 GeV of $M_{\rm t}$.

Summary: Thus in conclusion, both in the NMSSM and in the CPV-MSSM the moderately light charged Higgs that is allowed at moderately low values of $\tan\beta$, provides interesting and novel phenomenology at the LHC.

4. *CP-violating observables in Higgs boson decays at the LHC*

D Choudhury, R M Godbole and D J Miller

The aim of this subgroup was to construct Higgs sector observables which are zero in models where CP is conserved but may be non-zero if CP is violated. This is an intriguing question, since the scalar nature of the Higgs boson ensures that there is no correlation between its production and decay processes. For example, if we consider a subprocess $gg \to H \to \gamma\gamma$, we will have (for a narrow Higgs resonance)

$$\begin{aligned}|M(gg \to H \to \gamma\gamma)|^2 &= |M(gg \to H) \times M(H \to \gamma\gamma)|^2 \\ &= |M(gg \to H)|^2 \times |M(H \to \gamma\gamma)|^2\end{aligned}$$

indicating that there is no correlation.

In general, we need at least three directions to construct a CP-odd observable such as $\vec{a}\cdot(\vec{b}\times\vec{c})$, where the three vectors $\vec{a}$, $\vec{b}$ and $\vec{c}$ may be momenta or polarization vectors. For Higgs bosons, of course, there is no polarization vector, and hence, the number of channels at the LHC is severely limited. In fact, we must rely on Higgs boson decays to vector bosons, since they would have polarization vectors.

The MSSM is, obviously, the first consideration, since it allows us to have a CP-violating Higgs sector. However, the HVV vertices ($V = W, Z$) in the MSSM have the CP-conserving form $g_{\mu\nu}V^\mu V^\nu H$ at all orders. Hence, we must rely on the $H\bar{f}f$ vertices for CP-violation. Perhaps the simplest such possibility is to consider the process $gg \to H\bar{b}$ and construct a variable such as $(\vec{p}_b \times \vec{p}\,'_b) \cdot (\vec{p}_g - \vec{p}\,'_g)$, which is CP-violating. In practice, however, the two gluons are indistinguishable, so the average of this would always vanish. If we consider, instead, a similar process $q\bar{q} \to H\bar{b}$, then, in principle, the quark and antiquark are distinguished by their rapidity, but again the effect is likely to be too small for observation. Therefore, we really need to rely on a process which does not use the initial state partons, but still has plenty of other particles, e.g. those in decay chains. An example of such a process is the one given in figure 6, where the basic process is a $t\bar{t}H$ production. Here a possible CP-violating asymmetry is $(\vec{p}_b \times \vec{p}\,'_b) \cdot (\vec{p}_{\ell^+} - \vec{p}_{\ell^-})$. It was planned to start by considering this process.

This requires a careful and complete calculation and a detailed simulation of both signal and background. The combinatoric background from the four b-quarks in the final states, the possible merging of b-jets and, of course, the b-tagging efficiency, are all likely to play an important part in the observability, or otherwise, of this process. Studies are still under way.

Another possibility is to consider a general HVV vertex and to write it in terms of all CP-conserving and CP-violating form factors. CP-violating observables may

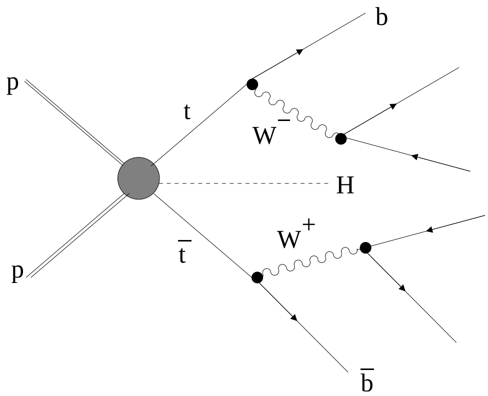

Figure 6. Associated production of a Higgs boson with a $t\bar{t}$ pair leading to possible CP-violating observables. The $W^{\pm}$ can decay into either a $\ell^{\pm}\nu_{\ell}$ pair, or into a qq' pair and the Higgs boson can decay into a $b\bar{b}$ pair (not shown).

arise from the interference of these two kinds of contributions. This project has been undertaken and is reported in the next subsection.

5. *CP-violating Higgs bosons decaying via $H \to ZZ \to 4$ leptons at the LHC*

R M Godbole, D J Miller, S Moretti and M M Mühlleitner

Here we study the decay of a Higgs boson to a pair of real and/or virtual Z bosons which subsequently decay into pairs of fermions, $H \to ZZ \to (f_1\bar{f}_1)(f_2\bar{f}_2)$, where f_1 and f_2 are distinguishable. This channel is particularly important at the LHC for Higgs masses $M_{\rm H} > 2M_Z$, where the Z bosons are produced on-shell, but is also of use for smaller Higgs boson masses where one of the Z bosons must be virtual [21].

To do a model-independent analysis we examine the most general vertex for a spin-0 boson coupling to two Z bosons, including possible CP-violation, which can be written as

$$\frac{ig}{m_Z \cos\theta_{\rm W}}[\, a\, g_{\mu\nu} + b\,(k_{2\mu}k_{1\nu} - k_1\cdot k_2 g_{\mu\nu}) + c\,\epsilon_{\mu\nu\alpha\beta}k_1^{\alpha}k_2^{\beta}], \tag{7}$$

with k_1 and k_2 the four-momenta of the two Z bosons, and $\theta_{\rm W}$ the weak-mixing angle. The form factors b and c may be complex, but since an overall phase will not effect the observables studied here, we are free to adopt the convention $a \in \Re$. These form factors can arise from radiative loop corrections or from new physics at the TeV scale, i.e., from higher-dimensional operators [22], and may themselves be functions of the momenta. The terms associated with a and b are CP-even, while that associated with c is CP-odd. $\epsilon_{\mu\nu\alpha\beta}$ is totally antisymmetric with $\epsilon_{0123} = 1$. CP-violation will be realized if at least one of the CP-even terms is present (i.e. either $a \neq 0$ and/or $b \neq 0$) and c is non-zero. In the following, for the sake of simplicity, we will always assume $b = 0$.

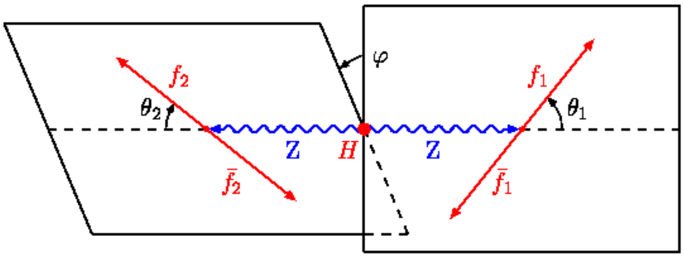

Figure 7. The definition of the polar angles θ_i $(i = 1, 2)$ and the azimuthal angle φ for the sequential decay $H \to Z^{(*)}Z \to (f_1\bar{f}_1)(f_2\bar{f}_2)$ in the rest frame of the Higgs boson.

For $b = 0$ this differs from the vertex of refs [23,24] in the CP-odd term by a factor of 2, and differs from that of refs [25–28] in the choice of m_Z as a normalization factor instead of $m_{\rm H}$. (For further related studies relevant to the LHC, see also refs [22,29–31]; for those relevant to e^+e^- colliders, see refs [32–37]; for a study at a photon collider, see ref. [38].)

The Standard Model at tree-level is recovered for $a = 1$ and $b = c = 0$, which is obviously CP-conserving. Nevertheless, it is interesting to ask if LHC will be sensitive to any exotic new physics which might provide a CP-violating HZZ vertex of this form.

The distributions sensitive to CP-violation: In order to fully test for the occurrence of CP-violation in the HZZ vertex it is helpful to find asymmetries which probe the real and imaginary parts of c. The real part of c is probed by any observable which is CP-odd and $\tilde{T}$-odd (where $\tilde{T}$ denotes pseudo-time-reversal, which reverses particle momenta and spin but does not interchange initial and final states), while the imaginary part is probed by any observable which is CP-odd and $\tilde{T}$-even. The non-vanishing of the CP$\tilde{\rm T}$-odd coefficients is related to the presence of absorptive parts in the amplitude [39].

An observable sensitive to $\Im m(c)$ can be found by looking at the polar angular distributions of the process. We denote the polar angles of the fermions f_1, f_2 in the rest frames of the Z bosons by θ_1 and θ_2 and define

$$O_1 \equiv \cos\theta_1 = \frac{(\vec{p}_{\bar{f}_1} - \vec{p}_{f_1}) \cdot (\vec{p}_{\bar{f}_2} + \vec{p}_{f_2})}{|\vec{p}_{\bar{f}_1} - \vec{p}_{f_1}||\vec{p}_{\bar{f}_2} + \vec{p}_{f_2}|}, \tag{8}$$

where $\vec{p}_f$ are the three-vectors of the corresponding fermions with $\vec{p}_{f_1}$ and $\vec{p}_{\bar{f}_1}$ in their parent Z's rest frame but $\vec{p}_{f_2}$ and $\vec{p}_{\bar{f}_2}$ in the Higgs rest frame (see figure 7). The angular distribution in θ_i $(i = 1, 2)$ for a CP-odd state is $\sim(1 + \cos^2\theta_i)$, corresponding to transversely polarized Z bosons, which is very distinct from the purely CP-even distribution proportional to $\sin^2\theta_i$ for longitudinally polarized Z bosons in the large Higgs mass limit [32,33]. $\Im m(c) \neq 0$ will introduce a term linear in $\cos\theta_i$ leading to a forward–backward asymmetry. The distribution for $\cos\theta_1$ is shown in figure 8 for a Higgs mass of 200 GeV and a purely scalar, purely pseudoscalar and CP-mixed scenario. The asymmetry is absent if CP is conserved (for both CP-odd

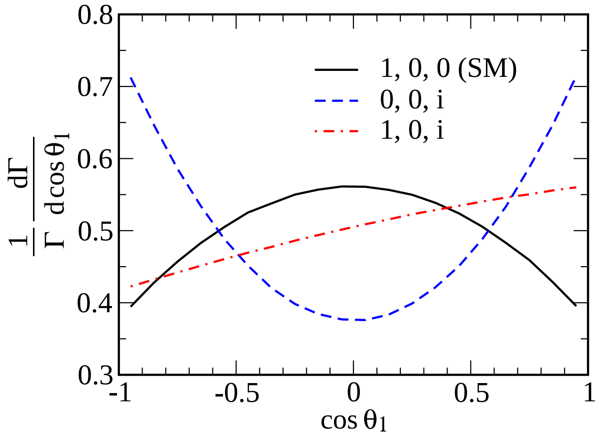

Figure 8. The normalized differential width for $H \to ZZ \to (f_1\bar{f}_1)(f_2\bar{f}_2)$ with respect to the cosine of the fermion's polar angle. The solid curve shows the SM ($a = 1$, $b = c = 0$) while the dashed curve is a pure CP-odd state ($a = b = 0$, $c = i$). The dot–dashed curve is for a state with a CP-violating coupling ($a = 1$, $b = 0$, $c = i$). One can clearly see an asymmetry about $\cos\theta_1 = 0$ for the CP-violating case.

and CP-even states) but is non-zero if $\Im m(c) \neq 0$ while simultaneously $a \neq 0$. This may then act as a definitive signal of CP-violation in this vertex. However, note that this observable requires one to distinguish between f_1 and $\bar{f}_1$.

To quantify this we define an asymmetry by

$$\mathcal{A}_1 = \frac{\Gamma(\cos\theta_1 > 0) - \Gamma(\cos\theta_1 < 0)}{\Gamma(\cos\theta_1 > 0) + \Gamma(\cos\theta_1 < 0)}. \tag{9}$$

In the case of no CP-violation $\mathcal{A}_1 = 0$, whereas any significant deviation from zero will be a sign that CP is violated. Figure 9(left) shows the value of $\mathcal{A}_1$ for a Higgs mass of 200 GeV as a function of the ratio $\Im m(c)/a$. The value $\Im m(c)/a = 0$ corresponds to the purely scalar state whereas $\Im m(c)/a \to \infty$ to the purely CP-odd case. It is clear from eq. (9) that $\mathcal{A}_1$ is sensitive only to the relative size of the couplings since any factor will cancel in the ratio. We find that the asymmetry is maximal for $\Im m(c)/a \sim 1.4$ with a value of about 0.077.

In order to get the first rough estimate whether this asymmetry can be measured at the LHC we calculate the significance with which a particular CP-violating coupling would manifest at the LHC. In the purely SM case, we assumed that 100 fb^{-1} provide 180 signal events containing $H \to ZZ \to 4$ leptons after cuts to remove background [21] (all production channels) with 100 fb^{-1} of data. We then divide this number by two to provide an estimate for $H \to ZZ \to e^+e^-\mu^+\mu^-$ (since we need to distinguish the leptons) and scaled this number up to 300 fb^{-1} (i.e. giving 270 events). The number of events for the CP-violating case has been obtained by multiplying the number of SM events by the ratio of CP-violating to SM cross-sections. We are therefore assuming the SM value for the CP-even coefficient, i.e. $a = 1$. For simplicity we assume that the charge of the particles is unambiguously determined.

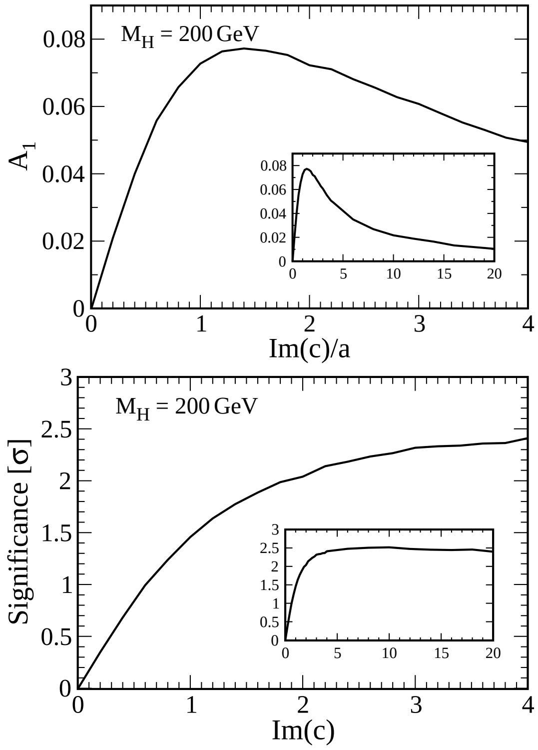

Figure 9. Top: The asymmetry given by eq. (9) as a function of the ratio $\Im m(c)/a$, for a Higgs boson of mass 200 GeV. Bottom: The number of standard deviations the asymmetry deviates from zero as a function of $\Im m(c)$. The inserts show the same quantities for a larger range of $\Im m(c)$.

Figure 9(bottom) shows the significance as a function of $\Im m(c)$, calculated according to $\mathcal{A}_1\sqrt{N}$ where N is the number of expected events. The maximum of the curve is slightly shifted to higher values of $\Im m(c)/a$ compared to figure 9(top) due to the increasing Higgs decay rate with rising pseudoscalar coupling. The curve shows that, even in the best case scenario, the significance is always less than 3σ. So evidence for CP-violation cannot be obtained in this channel without more luminosity. However, since one does not need to distinguish f_2 and $\bar{f}_2$ one could also consider using jets instead of muons, i.e. $H \to ZZ \to l^+l^-jj$, to increase the statistics. This process deserves further study.

To probe $\Re e(c)$ we require an observable which is CP-odd and $\tilde{\text{T}}$-odd, so we choose to define

$$O_2 \equiv \frac{(\vec{p}_{\bar{f}_1} - \vec{p}_{f_1}) \cdot (\vec{p}_{\bar{f}_2} \times \vec{p}_{f_2})}{|\vec{p}_{\bar{f}_1} - \vec{p}_{f_1}||\vec{p}_{\bar{f}_2} \times \vec{p}_{f_2}|}. \tag{10}$$

The dependence of the differential width on this observable is plotted in figure 10 but while an asymmetry is indeed present, it is very small and will be difficult to see in practice. The corresponding asymmetry is

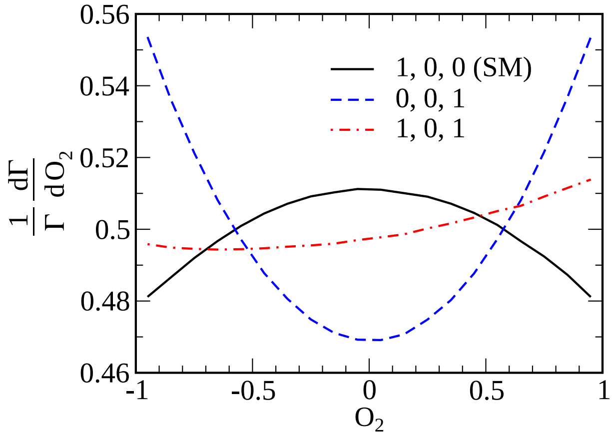

Figure 10. The normalized differential width for $H \to ZZ \to (f_1\bar{f}_1)(f_2\bar{f}_2)$ with respect to the observable O_2 (see text). The solid curve shows the SM ($a = 1$, $b = c = 0$) while the dashed curve is a pure CP-odd state ($a = b = 0$, $c = 1$). The dot-dashed curve is for a state with a CP-violating coupling ($a = 1$, $b = 0$, $c = 1$). Again one sees an asymmetry about zero for the CP-violating case.

$$\mathcal{A}_2 = \frac{\Gamma(O_2 > 0) - \Gamma(O_2 < 0)}{\Gamma(O_2 > 0) + \Gamma(O_2 < 0)}, \tag{11}$$

which is plotted in figure 11(top) as a function of $\Re e(c)/a$. The significance (as calculated for $\mathcal{A}_1$ above) is shown in figure 11(bottom). The significance is always very small, and it is difficult to see how this could provide useful information. In this case one cannot exploit the decay of Higgs bosons to jets since one must also distinguish f_2 and $\bar{f}_2$.

Another distribution sensitive to CP-violation is the azimuthal angular distribution $\mathrm{d}\Gamma/\mathrm{d}\varphi$ where φ denotes the angle between the planes of the fermion pairs stemming from the Z boson decays, (see figure 7), whereas the purely SM case shows a distribution

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\varphi} \sim 1 + A\cos\varphi + B\cos 2\varphi, \tag{12}$$

where the coefficients A and B are functions of the Higgs and Z boson mass (see ref. [24]), in the purely pseudoscalar case

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\varphi} \sim 1 - \frac{1}{4}\cos 2\varphi. \tag{13}$$

In the CP-violating case we must include contributions from both the scalar and pseudoscalar couplings which will alter this behaviour. Knowing the Higgs mass from previous measurements, any deviation from the predicted distribution in the scalar/pseudoscalar case will be indicative of CP-violation. This can be inferred from figure 12 which shows the azimuthal angular distribution for $M_{\mathrm{H}} = 200\,\mathrm{GeV}$

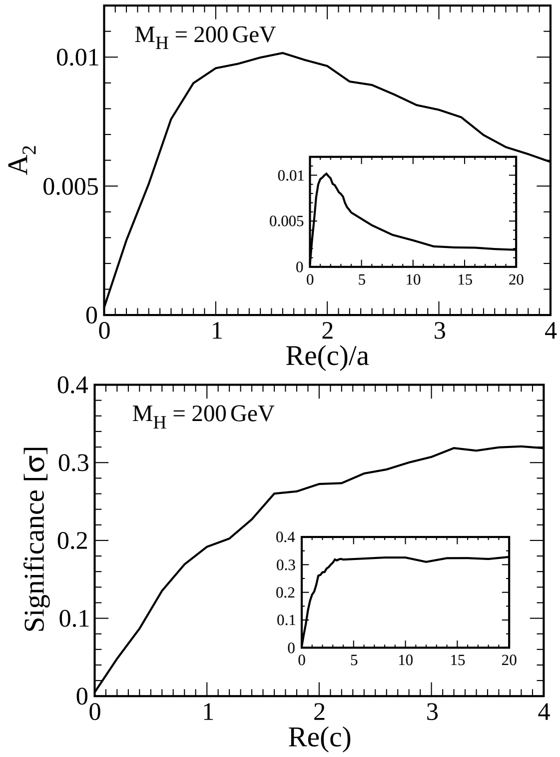

Figure 11. Top: The asymmetry given by eq. (11) as a function of the ratio $\Re e(c)/a$, for a Higgs boson of mass 200 GeV. Bottom: The number of standard deviations the asymmetry deviates from zero as a function of $\Re e(c)$. The inserts show the same quantities for a larger range of $\Re e(c)$.

in the SM case, for a CP-odd Higgs boson and two CP-violating cases. The purely CP-odd curve will always show the same behaviour independently of the value of c since the curves are normalized to unit area. Therefore, a special value of c could not fake the flattening of the curve appearing in the CP-violating examples. This flattening even leads to an almost constant distribution in φ for the case $c/a = 1$. It should be kept in mind, though, that this method cannot be applied for large Higgs masses where the φ dependence disappears in the SM. One must also beware of degenerate Higgs bosons of opposite CP; since one cannot distinguish which Higgs boson is in which event, one must add their contributions together, possibly mimicking the effect seen above.

This procedure is similar to that of refs [28,30] where log-likelihood functions were constructed and minimized to extract the coefficients in the vertex or yield exclusion contours.

The next step will be to study in a more realistic simulation how well the φ distribution can be fitted at the LHC and hence to which extent CP-violation can be probed in the azimuthal angular distribution.

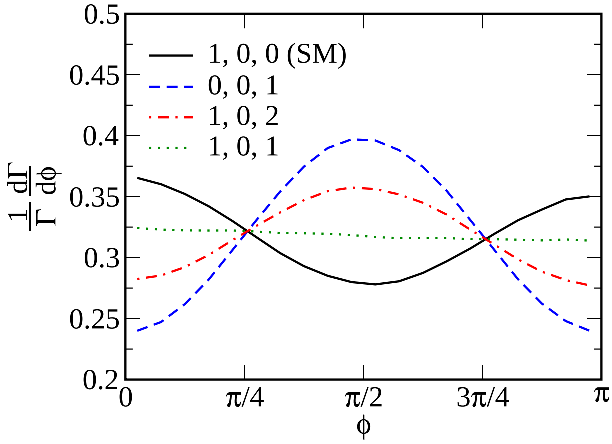

Figure 12. The normalized differential width for $H \to Z^{(*)}Z \to (f_1\bar{f}_1)(f_2\bar{f}_2)$ with respect to the azimuthal angle φ. The solid curve shows the SM ($a = 1$, $b = c = 0$) while the dashed curve is a pure CP-odd state ($a = b = 0$, $c = 1$). The dot–dashed curve and the dotted curve are for states with CP-violating couplings $a = 1$, $b = 0$ with $c = 2$ and $c = 1$, respectively.

Summary and outlook: We have studied the decays of Higgs bosons into a pair of Z bosons, which subsequently decay into leptons, for a general HZZ coupling at the LHC. We examined CP-violating asymmetries which probe the real and imaginary couplings of the CP-odd term. We found that the asymmetries produced are small and will not provide evidence of CP-violation at the LHC without higher luminosity. However, it may be possible to exploit other channels, such as Higgs decays to leptons and jets, to increase significances. We also examined the dependence on the azimuthal angle between the lepton planes, which is similarly indicative of CP-violation. Further studies of this azimuthal angle and the extension to arbitrary higher 'Higgs' spin will be the subject of future work.

6. *Other projects and discussions*

Some of the other possible projects and topics of discussions taken up in the working group are:

(1) *Identification of gluino decay through like-sign stop cascades* – B Allanach, D Choudhury and D P Roy

One can consider the stop coannihilation scenario with a stop-LSP mass difference of 20–30 GeV. If a gluino pair is produced in the LHC and the gluinos decay to top-stop pairs [40], the semileptonic decays of the top quark could lead to like-sign dileptons, which would be ultimately traceable to the Majorana nature of the gluinos. A more detailed study is intended, where c-quark plus LSP final states as well as three- and four-body stop decays are considered.

(2) *Detection of the Higgs through its tau-muon decay* – D Zeppenfeld, R Vaidya, M Guchait, S D Rindani and D Miller

The rare decay $H^0 \to \tau^{\pm}\mu^{\mp}$ could, if observable, provide quite spectacular signals for the Higgs boson. Preliminary studies carried out at the workshop, however, showed that the branching ratio is too small to produce observables which could be detected at the LHC. No follow-up study is, therefore, contemplated.

(3) *Collider signals for little Higgs models with T-parity* – M Perelstein, S K Rai, R M Godbole, S Kraml and N Okada

In little Higgs models with T-parity (LHT models), a whole set of extra T-odd particles is postulated [41], of which the lightest is stable and would lead to missing energy signals rather similar to those of SUSY. The mass spectrum of the low-lying states in these models is different from SUSY, however, and it should be possible to distinguish the two models by some sort of end-point analysis. The project requires incorporation of LHT processes in a suitable event generator. Several possible strategies were discussed. The project promises to be of long-term interest.

To summarize, then, the working group on collider physics has identified several problems of interest, of which some have been worked out in detail, some have been projected and some are under intensive study. Many of these studies will ultimately lead to publications and, it may be hoped, to actual observation of signals when the LHC and ILC eventually come into operation.

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