Author(s): AMOL DIGHE, ANJAN GIRI, RUPAK DUTTA, NAVEEN GAUR,TIM GERSHON, DIPTIMOY GHOSH, XIAO-GANG HE, GEORGE W-S HOU, YONG-YEON KEUM, BHAVIK KODRAN, NAMIT MAHAJAN, JOAQUIM MATIAS, BARILANG MAWLONG, BASUDHA MISRA, RUKMANI MOHANTA, GAGAN MOHANTY and SUDHIR VEMPATI
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B Physics: WHEPP-XI working group report

AMOL DIGHE[1,*], ANJAN GIRI[2], RUPAK DUTTA[3], NAVEEN GAUR[4],
TIM GERSHON[5], DIPTIMOY GHOSH[1], XIAO-GANG HE[6],
GEORGE W-S HOU[6], YONG-YEON KEUM[7], BHAVIK KODRANI[8],
NAMIT MAHAJAN[8], JOAQUIM MATIAS[9], BARILANG MAWLONG[10],
BASUDHA MISRA[3], RUKMANI MOHANTA[11], GAGAN MOHANTY[1] and
SUDHIR VEMPATI[10]

[1]Tata Institute of Fundamantal Research, Homi Bhabha Road, Colaba, Mumbai 400 005, India
[2]Indian Institute of Technology Hyderabad, Yeddumailaram 502 205, India
[3]Institute of Mathematical Science, CIT Campus, Taramani, Chennai 600 113, India
[4]University of Delhi, Delhi 110 007, India
[5]University of Warwick, Coventry CV4 7AL, UK
[6]National Taiwan University, Roosevelt Road, Taipei, 10617 Taiwan, ROC
[7]Institute for the Early Universe, Ewha Womans University, Seoul 120 750, Korea
[8]Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India
[9]Universitat Autonoma de Barcelona, E-08193 Barcelona, Spain
[10]Centre for High Energy Physics, Indian Institute of Science, Bangalore 560 012, India
[11]University of Hyderabad, Hyderabad 500 046, India
*Corresponding author. E-mail: amol@theory.tifr.res.in

Abstract. We present the report of the *B* physics working group of the Workshop on High Energy Physics Phenomenology (WHEPP-XI), held at the Physical Research Laboratory, Ahmedabad, in January 2010.

Keywords. *B* decays; charge-parity violation; physics beyond the Standard Model.

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1. Introduction

The study of flavour physics has been instrumental for a better understanding of the Standard Model (SM) of particle physics. In particular, our understanding of the charge-parity (CP) violation has been shaped by observations in the flavour sector: starting from the discovery of CP violation in the K mesons, to the observation of CP violation in the B mesons and the precision testing of the Kobayashi–Maskawa mechanism of CP violation. The decays of B mesons are prime candidates to look for indirect signatures of physics beyond the SM.

The two B-factories, BaBar and Belle, which are dedicated machines that have produced $\sim 10^9$ B mesons, have already explored various facets of the decays of B^+ and $B_{\rm d}$ mesons. In addition, the Tevatron experiments CDF and DØ have provided data on the $B_{\rm s}$ decays. Through the measurements of decay rates, asymmetries and angular distributions in many decay channels, these experiments have provided precision tests of the SM.

Though all the B decay measurements till now have been consistent with the SM [1,2], recently there have been a number of hints for new physics (NP) beyond the Standard Model (BSM), the most notable ones being through the angular distribution in $B_{\rm s} \to J/\psi\phi$ [3], direct CP asymmetries in $B \to K\pi$ decays [2], the forward–backward asymmetry in $B_{\rm d} \to K^*\mu^+\mu^-$ [4], and the dimuon asymmetry in semileptonic B decays [5]. Another observable that shows tension with the SM is the isospin asymmetry in $B \to K^*\mu^+\mu^-$ [6,7]. Although it is too early to claim any of the above signals as conclusive, further data may give us a clear evidence of such BSM physics.

While a large fraction of the data already obtained from the B factories and Tevatron still remain to be analysed, the experiments at the LHC–ATLAS, CMS and LHCb (a dedicated flavour physics experiment) – will soon have enough data to compete with the earlier experiments for some of the most sought-after measurements in the flavour sector. Indeed, we may expect to have something exceptionally new in WHEPP-XII, the next edition of the workshop.

We now present the highlights of the theoretical and experimental review talks presented during the workshop. Thereafter we enlist and mention briefly the specific topics discussed in the working group; these discussions were typically initiated by one of the participants, who gave a short presentation and led the discussions. Finally, we mention the projects shortlisted for further work during and after the workshop, and summarize.

2. Theoretical and experimental review of *B* Physics

2.1 *B Physics and the high energy frontier*

George W-S Hou

After an introduction to CP violation, the speaker focussed on three of the CP quantities that involve $b \to s$ transitions and have the potential of probing new physics: ΔS, $\sin 2\phi_{B_{\rm s}}$, and $\Delta A_{K\pi}$. He also talked about the probes of charged Higgs from B decays and looking for new physics signals in the semileptonic rare B decays.

Measurement of the angle $\beta = \text{Arg}[-(V_{\rm cb}V^*_{\rm cd})/(V_{\rm tb}V^*_{\rm td})]$ of the Cabibbo–Kobayashi–Maskawa (CKM) unitarity triangle [7a] has perhaps been the most important measurement coming out of the B factories. In the SM, 2β is the $B_{\rm d}$–$\bar{B}_{\rm d}$ mixing phase, and its cleanest and most accurate measurement is obtained from the time-dependent CP asymmetry in the 'gold-plated' mode $B_{\rm d} \to J/\psi K_{\rm S}$, which is expected to be $\sin 2\beta$. This angle can be measured in many decay modes, where the interference between the channels $B_{\rm d} \to f_{\rm CP}$ and $B_{\rm d} \to \bar{B}_{\rm d} \to f_{\rm CP}$ appears. (Here $f_{\rm CP}$ is the final state that is a CP eigenstate.) Each of these decays measures S, the CP asymmetry due to mixing, which reduces to $\sin 2\beta$ in the SM. While the measurement of this quantity in the modes involving a $b \to c\bar{c}s$ transition is consistent with the measurements of the other parameters of the unitarity triangle, there appears to be a deviation (ΔS) from the SM in some of the modes involving a $b \to s\bar{s}s$ transition [2]. Though the deviations are not too significant at this time, more data expected from the upcoming Super-B/Belle2 will reduce the error bars and the presence of new physics will be severely tested.

The B_s–$\bar{B}_s$ mixing phase ϕ_{B_s} is predicted to be close to zero in the SM. However, the current measurements of this quantity, as well as that of the width difference $\Delta\Gamma_s$ in the B_s system by the CDF and DØ collaborations through the $B_s \to J/\psi\phi$ mode [3], show about 2σ deviation from the SM expectation. Many new physics candidates have been proposed for explaining the significant value of ϕ_{B_s}.

In the SM, the difference between the direct CP asymmetries in $B^+ \to K^+\pi^0$ and $B^0 \to K^+\pi^-$, termed as $\Delta A_{\rm CP}$, is expected to vanish in the naive factorization approach. Currently, experiments show $\Delta A_{\rm CP} = 0.147 \pm 0.028$, which is a 5σ deviation from zero [2]. It is not clear whether this deviation is due to new physics, or due to some hadronic effects that are not well understood. For example, the SM prediction mentioned above neglects the contribution from electroweak penguin ($P_{\rm EW}$) and colour-suppressed tree (C) diagrams, which is the naive expectation. Even with improved schemes of calculating these quantities, like QCD-improved factorization [8,9], $\Delta A_{\rm CP}$ would be hard to explain as it would require large imaginary values for $P_{\rm EW}$ and C [10]. Moreover, if $P_{\rm EW}$ were the explanation, one would have been able to see some evidence from ratios of the form $\mathcal{B}(B^+ \to \pi K)/\mathcal{B}(B^0 \to \pi K)$ or $\mathcal{B}(B^+ \to \rho K)/\mathcal{B}(B^0 \to \rho K)$, which is not found. On the other hand, if C were the explanation, it would imply a breakdown of the power-counting in the context of soft collinear effective theory (SCET), which has been observed to hold in other modes [11]. The perturbative QCD framework [12,13] for calculating decay rates allows an explanation through higher order corrections [14,15], but this is still a bit ad-hoc. Thus, the real explanation of this $\Delta A_{K\pi}$ anomaly still eludes us.

New physics arising in electroweak penguins can also manifest itself in the rare semileptonic decay modes like $B \to K^{(*)}\ell^+\ell^-$. Indeed, the forward–backward asymmetry $A_{\rm FB}(B \to K^*\mu^+\mu^-)$ measured at Belle shows a deviation from the SM [4]. This asymmetry is a result of the interference between photonic and Z-penguin contributions and is sensitive to new physics. A measurement of $B \to K^*\nu\bar{\nu}$ would be a clean probe of such new physics. The current upper bounds are a factor of ∼5 above the SM predictions, but more data would bring them down to the SM level, thus allowing a precision measurement of this decay mode.

The calculations for the decay rate of the inclusive radiative decay mode $B \to X_s\gamma$ are now available at the next-to-next-to-leading order (NNLO) [16]. Combining these with the recent measurements [2] constrains the mass of a charged Higgs in type-II two-Higgs-doublet models (2HDM) to be greater than 300 GeV at 95% CL [17]. Another mode that is highly sensitive to the charged Higgs is $B^+ \to \tau^+\nu$, since H^+ here appears at the tree level [18]. Here, the measurement of the branching ratio seems to differ from the fit to the SM parameters performed excluding this mode, which remains to be explained. Although the measurements from these two decay modes are consistent within the context of a charged Higgs, they would imply a large value of $\tan\beta$ [19].

With the hints for new physics coming from many measurements, one needs to look at ways of extending the SM so that the data can be explained. One of the viable new physics candidates is a fourth generation of quarks: it is still allowed, and can in fact help in explaining some of the anomalies mentioned above. For example, the ΔS and ϕ_{B_s}

anomalies are easily resolved with a fourth generation, which allows three more mixing angles and two more mixing phases in the quark mixing matrix. Some other candidates are the right-handed currents that can be explained through the time-dependent CP asymmetry in $B \to (K_S\pi^0)_{K^*}\gamma$ [20,21], and new scalar interactions that can affect the decay rate of $B_s \to \mu^+\mu^-$. In all these cases, we may be only a few years away from learning the true nature of new physics [22].

2.2 *B Physics experiments: Current status and future prospects*

Tim Gershon

Tim Gershon presented the latest results from the B factory data and an overview of the experimental scenario in B physics, including future prospects. The data taking in BaBar (SLAC, USA) was over in 2008 and Belle (KEK, Japan) will be closed in 2010 to enable Belle2 to come up in time. Super-B is a planned e^+e^- facility in Italy, which may also start taking data after five years or so from now. CDF and D0 experiments at Tevatron are running at present and providing us valuable information in many aspects of particle physics along with the data in B sectors. These hadron collider experiments may be closed by the end of 2011. The LHCb experiment has already started and its first upgrade is planned to be after around five years. The ATLAS and CMS experiments also offer opportunities for B physics even at low luminosities during the first few years of the LHC. Thus we will be receiving complementary information on B decays from both leptonic and hadronic colliders.

The speaker presented the measurements of the angles of the unitarity triangle, β, α and γ. The world average of $\sin 2\beta$ is now 0.673 ± 0.023 [2], which is dominated by the measurement of the gold-plated $B_d \to J/\psi K_S$ decay. The measurements of this quantity through many different channels are roughly compatible with each other at the moment. However, more data from Super-B and Belle2 may be able to shed light on whether the current subcritical hints are real or not. The measurement of the angle $\alpha = \left(89.0^{+4.4}_{-4.2}\right)^\circ$ [2] is dominated by $B \to \rho\rho$ decays, whereas the measurement of γ comes from $B \to DK$ decays, where one needs to combine the decays of D to CP eigenstates [23,24], to colour-suppressed final states like $K\pi$ [25], and through the Dalitz plot analysis of $D \to K_S\pi\pi$ [26]. This combination is a bit controversial in the sense that the results of the two main fitting groups, UTfit [$\gamma = (78 \pm 12)^\circ$] and CKMfitter [$\gamma = (73^{+19}_{-24})^\circ$], though consistent, do not agree with each other, though they use the same data.

Apart from the angles of the 'standard' unitarity triangle, which correspond to CP violation in the K and B_d system, another important quantity is the B_s–$\bar{B}_s$ mixing phase ϕ_{B_s} that is measured through the angular distribution in $B_s \to J/\psi\phi$. This corresponds to one of the angles of the 'squashed' unitarity triangle. It is predicted to be $\phi_{B_s} = -0.038 \pm 0.002$ in the SM. However, the combined measurements from CDF and DØ indicate a much larger value, thus giving a hint of NP. Further data from Tevatron, and from the LHCb experiment, is needed to say anything definite about this. If Super-B or Belle2 run at the $\Upsilon(5S)$ resonance for a fraction of their run, they may also help in resolving this issue.

Among the magnitudes of the CKM matrix elements, those that involve only the first and the second generation are well measured. While it is not possible currently to directly measure the elements involving the t quark, the measurements of $|V_{cb}|$ and $|V_{ub}|$ have seen some progress in recent years. The current value of $|V_{\mathrm{cb}}|$ is $(41.6 \pm 0.6)^{\circ}$, obtained from the inclusive semileptonic decay $B \to X_c \ell \nu$ [2]. The measurement of $|V_{\mathrm{ub}}|$ involves inclusive as well as exclusive semileptonic modes ($B^0 \to X_u \ell^+ \nu$ and $B \to \pi^+ \ell^+ \nu$, respectively) and different theoretical approaches give different – though consistent with each other – fits: $4.06 \pm 0.15^{+0.25}_{-0.27}$ and $4.25 \pm 0.15^{+0.21}_{-0.17}$ [2]. There are significant experimental and theoretical problems in combining different measurements to come up with a single average for $|V_{\mathrm{ub}}|$.

Rare decays could be very incisive probes of new physics. While $B \to X_{\mathrm{s}} \gamma$ decay rate is consistent with the SM, the photon polarization measurements at the LHCb may be able to test for NP through the time-dependent asymmetry. The forward–backward asymmetry in $B \to K^* \mu^+ \mu^-$ has already given a hint of NP, which will need to be confirmed at the LHC. The upper bounds on the branching ratios of $B_{\mathrm{s/d}} \to \mu^+ \mu^-$ are less than two orders of magnitudes above the SM predictions. Various new physics scenarios (such as supersymmetry, extra-Z' boson model, extra-dimension scenarios, fourth generation, etc.) can provide such an enhancement, and can manifest themselves through this decay. There are thus ample opportunities for LHC and super-B factories to look for new physics.

3. Discussions initiated by short presentations

3.1 *Determination of CKM parameters*

A Dighe

Amol Dighe gave a short presentation on the measurement of CKM parameters, emphasizing the role of the angular distribution of $B_{\mathrm{s}} \to J/\psi \phi$ [27,28] in the determination of $\phi_{B_{\mathrm{s}}}$ and $\Delta\Gamma_{\mathrm{s}}$. The current best fit by CDF and DØ [3] in the $\Delta\Gamma_{\mathrm{s}}$–$\phi_{B_{\mathrm{s}}}$ parameter space indicates that, in addition to $\phi_{B_{\mathrm{s}}}$ being significantly more than the SM expectation, even $\Delta\Gamma_{\mathrm{s}}$ seems to have a high value. The common wisdom that $\Delta\Gamma_{\mathrm{s}}$ can only decrease in the presence of NP [29] applies only if new physics does not involve any intermediate light particles contributing to B_{s}–$\bar{B}_{\mathrm{s}}$ mixing. However, NP models that increase the decay rate $B_{\mathrm{s}} \to \tau\tau$ contribute to the absorptive part of B_{s}–$\bar{B}_{\mathrm{s}}$ mixing, and can enhance $\Delta\Gamma_{\mathrm{s}}$ all the way to its current experimental bound [30,31].

3.2 *Fourth generation of quarks*

A Giri

Anjan Giri gave a short account of the scenario with four quark generations, and possible problems in the flavour sector that can be looked at with its help. The SM with three generation of quarks and leptons has been very successful in explaining the data so far, but a fourth generation is still not excluded, even with the electroweak precision data. The fourth generation seems to be one of the simplest extensions of the SM which might be responsible for the deviations observed in some of the B physics measurements. While it is difficult to say anything with certainty at this moment, recent studies show that if the masses of the fourth generation quarks lie between 400 and 600 GeV (with the mass splitting around 50 GeV), then it is possible to account for most of the anomalies simultaneously [32,33].

3.3 *Perturbative QCD for calculating decay rates and CP asymmetries*

Y-Y Keum

Yong-Yeon gave two lectures on the perturbative QCD (pQCD) calculational techniques and also presented some recent results using the pQCD framework [12,13]. He elaborated on the basic differences between the pQCD framework and alternative ones like QCDF and SCET. In the naive factorization approach, the amplitude for a typical decay process involving two mesons in the final state is assumed to be the convolution of the respective hadron wave functions with the perturbative hard decay kernel, assuming that there are no gluon exchanges between the final-state hadrons. The wave functions and various form factors are the nonperturbative inputs obtained from lattice or light cone sum rule methods. The QCD factorization method includes the nonfactorizable corrections arising due to gluonic exchanges between the final-state hadrons as well, but the form factors are still treated as nonperturbative inputs and therefore universal in character. The pQCD approach, in contrast, advocates the idea that form factors can be reliably computed in perturbation theory and only the wave functions/parton distribution amplitudes are the basic nonperturbative inputs. It involves an expansion in $\Lambda_{\mathrm{QCD}}/m_{\mathrm{b}}$, $\alpha_{\mathrm{s}}(m_{\mathrm{b}})$ and $\alpha_{\mathrm{s}}(\sqrt{\Lambda_{\mathrm{QCD}}/m_{\mathrm{b}}})$, and has a predictive power up to the leading order (LO) in $1/m_{\mathrm{b}}$ and all orders in α_{s}, just like the QCDF approach [8,9].

Next-to-leading order (NLO) calculations in pQCD approach [14,15] show that the ΔA_{CP} problem can be resolved in the pQCD approach. However, here the results for $A_{\mathrm{CP}}(B^+ \to K^+\pi^0)$ do not agree with the calculations based on other approaches. So the jury is still out on this issue.

3.4 *Charge Higgs exclusion from B decays*

G Mohanty

Gagan Mohanty showed that if one combines the bounds in the m_{H^+}–$\tan\beta$ parameter space for a type-II two-Higgs doublet model from (i) $B \to X_{\mathrm{s}}\gamma$, (ii) $B \to D\tau\nu$ and (iii) $B \to \tau\nu$, then the excluded region is such that ATLAS cannot find such a charged Higgs even with an integrated luminosity of 30 fb^{-1} [19]. This shows that the indirect probes of NP by B decays are competitive with the direct probes at high energy colliders.

3.5 *Combining multiple experiments*

T Gershon

Tim Gershon, who is also a member of the heavy flavour averaging group (HFAG) [2], addressed some of the issues related to combining data from different experiments for fitting to a common parameter. The talk was of general interest as data from many independent channels are typically available for the same set of parameters, not just in B physics experiments but in almost all branches of high energy physics.

3.6 *Lepton flavour violating τ decays at Super-B*

S Vempati

Sudhir Vempati gave an account of the lepton flavour violating decays which can give us the signals of new physics, and which can be tested at the super-B factories. He focussed on the minimal flavour violation (MFV) scenario, explained its current status, and commented on how we can constrain its parameters with the future experiments [34].

3.7 *NP in charm couplings with FCNC in B decays*

X-G He

Xiao-Gang He presented a talk based on his recent work on charm couplings with flavour changing neutral B decays [35]. The possibility of new extra Z' boson and its implications were discussed later.

3.8 *Exclusive $B \to K^*\ell^+\ell^-$ decays*

J Matias

Joaquim Matias gave a review talk on charmless semileptonic B decays, where he pointed out that if the present indication for an anomalous forward–backward asymmetry is confirmed, it will mostly be due to new vector–axial vector interactions, though a combination of scalar–pesudoscalar and tensor interactions can also shift the position of ‘zero’ of the asymmetry substantially [36]. He also advocated some new observables available through the angular distribution of $B \to K^*(\to K\pi)\ell^+\ell^-$ at large recoil, which can easily be measured in the ongoing and future experiments. These new observables – the transverse asymmetries $A_{\mathrm{T}}^{(2,3,4,5)}$ – will be very helpful to identify specific signatures of new physics [37–40]. These observables have been computed in the framework of QCDF at NLO including Λ/mb corrections of order 10%. In particular, $A_{\mathrm{T}}^{(2)}$ may play an important role in the coming years, since it contains the most relevant information of A_{FB} (its zero), and moreover, it is also sensitive to right-handed currents in modulus and phase (as opposed to A_{FB}) with a minimal sensitivity to soft form factors. $A_{\mathrm{T}}^{(3,4)}$ offers sensitivity to the longitudinal spin amplitude of the K^*. Moreover, $A_{\mathrm{T}}^{(5)}$ exhibits robust predictions that can be tested at LHCb, like the value of its maximum in the SM which is unaffected by NLO corrections: deviations from this value would point towards contributions from the chirally flipped operator O'_{10}. The structure of these transverse asymmetries, together with the relatively less clean measurements of A_{FB} and the longitudinal polarization fraction f_{L}, may allow to design a decision tree to discriminate between different types of NP contributions to the Wilson coefficients.

4. Projects shortlisted in the working group

The following are the projects that were shortlisted for future work. Small subgroups of participants would take up some of them and carry on with the collaborations even after the workshop. Some of these investigations have already led to publications by the time these Proceedings are written.

4.1 *Determination of α with four generations*

The angle α of the unitarity triangle is determined mainly through $B \to \rho\rho$ by the angular analysis method. The main source of uncertainties is the contribution of penguin diagrams, which is hard to quantify. In addition, most of the analyses assume three generations. If indeed a fourth generation is present, is the quantity determined still equal to α? If not, can one estimate corrections to this quantity due to the additional quark generation? These questions may be addressed to start with, which will later on feed into a complete fit to parameters of a 4×4 quark mixing matrix.

4.2 *Longitudinal polarization $f_{\rm L}$ in $B \to \phi K^*$*

Longitudinal polarization (the fraction of events wherein the final-state particles are longitudinally polarized) in $B \to \phi K^*$ is expected to be close to unity, since one should have $1 - f_{\rm L} = f_{\rm T} \propto m_{K^*}^2/m_B^2$ [41,42]. However, experiments seems to prefer $f_{\rm T}/f_{\rm L} \simeq 1$ [43–45]. In the framework of the SM one can think of two possible mechanisms that could be responsible for this puzzle: penguin annihilation or rescattering effects. Indeed one can find pairs of decays such that the ratio $f_{\rm T}/f_{\rm L}$ in one decay can be related to the corresponding ratio in the other decay using penguin annihilation. Examples of these pairs are ($B_{\rm s} \to \phi\phi$, $B_{\rm d} \to \phi K^{0*}$) or ($B_{\rm s} \to \phi \bar{K}^{0*}$, $B_{\rm d} \to \bar{K}^{0*} K^{0*}$) [46].

4.3 $\Delta\Gamma_{\rm s}$ *enhancement*

It has been shown that NP models that contribute to $B_{\rm s} \to \tau\tau$ can enhance the width difference $\Delta\Gamma_{\rm s}$. Some of these models – for example scalar leptoquarks or R-parity violating supersymmetry – have already been discussed [30]. It was decided to check if any other viable models can give rise to significant enhancement in $\Delta\Gamma_{\rm s}$.

After the workshop, when DØ came out with the anomalous dimuon asymmetry in semileptonic B decays, it was observed [31] that the model with a third generation leptoquark can enhance $\Delta\Gamma_{\rm s}$ enough to account for both this anomaly as well as the measurement of this quantity through $B_{\rm s} \to J/\psi\phi$. It was also pointed out [47] that the width difference in the $B_{\rm d}$ system, which can be enhanced by similar models [30], can act as a stringent test of the SM.

4.4 *$B \to K^*\mu^+\mu^-$ observables*

In his talk, Joaquim Matias had pointed out certain observables in $B \to K^*\mu^+\mu^-$, which can be affected by new physics. A systematic study may be carried out which can indicate what kind of deviations from the SM would imply which kind of new physics. Such a survey has since been performed, not only for this decay but for all the decays of the form $b \to s\mu^+\mu^-$, which systematically calculated the effect of different Lorentz structures of new physics on the CP-conserving observables [48].

4.5 *Stringent bounds on charged Higgs from B physics data*

It has been pointed out recently [17,19,49,50] that the data from flavour physics leads to strict bounds in the m_{H^+}–$\tan\beta$ parameter space for type-II 2HDM models. This implies that the LHC experiments may not be able to see direct signals of a charged Higgs even with $\sim$30 fb^{-1} of data. This claim needs to be explored further for any loopholes. Of course, this claim is valid only for type-II 2HDM models. One can also ask the question: if indeed LHC observes a charged Higgs in the forbidden region, which other models could have given rise to this charged Higgs? Some Standard Models may be explored to find out what could mimic such a charged Higgs signal.

5. Summary

B physics has always been a subject driven by new experimental results, and more so in recent times when ever-increasing number of measurements are becoming available, some of them showing indications of new physics. The talks and discussions in the *B* physics working group were naturally focussed around the recent hints for BSM physics from the data. It is expected that some of the discussions and projects started during the workshop will give rise to successful collaborations and publications.

It may so happen that the Nature may not oblige us the way we expect the new physics to appear and in fact may even reveal something completely unexpected. In any case, it appears to be clear that there will be exciting new developments by the time of next WHEPP and we are eagerly looking forward to that.

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