Abstract: New Higgs scalars with masses up to 10 GeV are predicted in models such as the NMSSM, and in scenarios with hidden sectors that couple weakly to the Standard Model. Searches at B factories have resulted in tight constraints on such models. We review the recent searches and new results, and discuss the future outlook for this physics.

Keywords: dark matter; B-factory; particle searches

1. The B factories

The B factories: PEP-II at Stanford and KEK-B at Tsukuba, were built in the 1990s as asymmetric electron–positron colliders with a centre-of-momentum system energy around 10 GeV, aimed at producing large numbers of $B^0$ and $B^0$ mesons through the decay of the $\Upsilon(4S)$. Together with their associated detectors, BABAR and Belle, their goal was firstly to establish whether CP violation, which at the time had only been observed in $K^0$ mesons, also existed in the $B$ system, and secondly, if that were the case, to measure its effects to high accuracy in many different channels, to establish whether the theoretical explanation and prediction of Kobayashi and Maskawa (1973) that the effect was due to mixing between three quark generations, was correct and sufficient, or whether some further source of CP violation, perhaps, related to the cosmic matter–antimatter asymmetry, was needed.

This project was a spectacular success, and Kobayashi and Maskawa received the Nobel prize in 2008. As the press release put it, “As late as 2001, the two particle detectors BABAR at Stanford, USA and Belle at Tsukuba, Japan, both detected broken symmetries independently of each other. The results were exactly as Kobayashi and Maskawa had predicted almost three decades earlier” (Retrieved February 18, 2015).
2015, from http://www.nobelprize.org/nobel_prizes/physics/laureates/2008/press.html. A full account of the physics discoveries of both factories, and the unsuccessful attempt to find CP violation that could not be accommodated in the Kobayashi–Maskawa scheme, can be found in Bevan et al. (2014).

Although B physics was their primary purpose, the factories also produced many results in other areas of particle physics: charm and τ physics in particular; these can also be found in Bevan et al. (2014). The purpose of this note is to survey their impact on the subject of the conference: light Higgs bosons and dark matter candidates.

Although these machines are not at the “energy frontier” where most discoveries are made, they explore large new areas of the second “precision” frontier. The accurate measurement of CP violation in B mesons required high statistical precision from enormous samples of events. The design luminosities of $0.3 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ seemed very challenging when they were set, as the CLEO-II ring at Cornell and only achieved $8.5 \times 10^{32}$. That these goals were met and exceeded, with luminosities above $10^{34}$ being regularly achieved by both machines, is a matter of pride for the machine builders.

The data samples grew rapidly; the integrated luminosity is shown as a function of time in Figure 1. The events are ideal for many sort of physics studies. As these are $e^+e^-$ collisions, the interacting fundamental particles contain the full energy of the beam (unlike quarks in the LHC). There are no “spectator” effects, no multiple collisions and no “residual event”. The asymmetry of the collisions, the fact that the cms is moving in the lab at 0.5 c, though essential for B lifetime measurements, is not helpful in any other channel, but on the other hand, it is not a hindrance either. The detectors cover most, though not all, of 4π and comprise the usual layered structure of vertex chamber, tracking chamber, Cherenkov detector, electromagnetic calorimeter and hadron calorimeter/muon filter. The design was dictated by the needs of B physics program, and so the vertex detection is excellent, the electromagnetic calorimetry has very good energy resolution, and the K/π separation is exceedingly good. These features may be borne in mind when considering other physics analyses.

### 2. Dark matter particles

Astronomical observations of the motion of stars and galaxies have long suggested the existence of as yet unknown species of elementary particle. These are not part of the Standard Model, but the many Beyond-the-Standard-Model theories offer a wide range of candidates.

![Figure 1. The integrated luminosity for BABAR and Belle.](image-url)
The reason these have evaded detection so far may be due to their having a large mass: dark fermions, particularly those predicted by supersymmetry, generally fall into this category, and to discover these an energy frontier machine is needed. Or the dark matter particle(s) may be light, but have not yet been observed due to their weak couplings. However, in many models, the dark matter particle(s) is part of a whole sector of new particles, some of which could be detected.

The dark photon is one such candidate. If, as proposed by Fayet (1980), there is a sector of dark matter WIMP particles which do not decay to known particles due to conservation of some new charge, there can be a new $U_1$ gauge boson, the $A'$. Kinetic mixing generates a small coupling $\epsilon$, between this dark photon and the conventional photon. Such a particle is not itself dark, despite the name, but provides a “portal”, interacting with both the dark and the normal sectors. This particular model has aroused interest recently as it provides a possible explanation for the excess of positrons reported by AMS (Aguilar et al., 2013): dark fermions annihilate to produce dark photons, which then decay to particle/antiparticle pairs. However, to fit this explanation, the mass of the dark photon must be small, below a few GeV, or it would also give a cosmic $\bar{p}$ excess, which is not seen.

In such a model the dark photon mass is generated by a Higgs mechanism, and there is a new Higgs particle, $h'$, the dark Higgs; this is also a “portal” particle. Similar particles occur in other models with two or more Higgs doublets, as a light scalar $h$ or pseudoscalar $A^0$. The experimental searches are sensitive to all such particles: basically a result detects, or puts a limit on, the presence of a particle at a particular mass decaying into two fermions; this can then be interpreted in terms of the parameters of a particular model.

This note covers searches for particles through their production; there is also a wealth of evidence from indirect searches, particularly FCNC $b$ decays, where virtual BSM particles can interfere with the $W/Z$. These decays, such as $B \rightarrow K^{+}\nu\bar{\nu}$ and $B \rightarrow \tau\nu$, provide powerful constraints on the models, which can be found in Bevan et al. (2014).

3. Searches
We consider searches in five channels: ISR production, $\Upsilon$ decays, dark Higgsstrahlung, narrow gauge bosons and long-lived particles. Full details can be found in the references.
3.1. ISR production
If there is a dark photon (or other state coupling to electrons), with a mass below the cms energy, then initial state radiation down to that mass, as depicted in Figure 2, has a characteristic monochromatic photon as a signature, as well as any decay products from the particle itself. This enables a scan of the mass region for any possible $A'$ or similar particle that decays to a state with a clear signature, such as two muons or two electrons.

BABAR has performed this analysis (Lees et al., 2014) and there is no sign of any peak in the range $0.02 \text{ GeV} < m_{A'} < 10.2 \text{ GeV}$ in either channel (apart from the well-known $J/\psi$ and $\psi'$ resonances), as can be seen in Figure 3. There is a disagreement in the low-mass electron pairs, but this particular Monte Carlo is not tuned for this region. The Monte Carlo is not used in the extraction of the rests.

From this lack of signal, one can set upper limits on the dark matter coupling parameter $\epsilon$ at the level on level $10^{-3} - 10^{-4}$, depending on the mass of the $A'$. The interesting point about this exclusion plot (Figure 4) is that it excludes almost all of the remaining regions of parameter space favoured by $g_\mu - 2$ discrepancy.

3.2. Production in $\Upsilon$ decays
The $\Upsilon(1S)$ is narrow, due to Zweig’s rule, and rare decays can in principle be observed. The $b$ and $\bar{b}$ quarks may produce a dark photon (or other particle), emitting a monochromatic photon to take away the excess energy, as depicted in Figure 5. The $A'$ decays to a fermion–antifermion pair. The object produced...
could be a dark photon or a NMSSM CP-odd Higgs: the difference lies in the couplings to the different channels.

Searches can be performed by running at the $\Upsilon(1S)$ energy and looking for the channels in question. A refinement of this technique is to run at the $\Upsilon(2S)$ or $\Upsilon(3S)$ energy, and the radiative decay $\Upsilon' \rightarrow \Upsilon(1S)\pi^+\pi^-$ provides a characteristic tag, in the form of the two slow pions, that show that a $\Upsilon(1S)$ has been formed. These events are then analysed for a $\gamma f\bar{f}$ signal.

$\text{BABAR}$ have performed a complete set of such tagged searches in the different channels, including invisible decays to light dark matter. The final analysis, $A \rightarrow D\bar{D}$ has been recently completed (Lees et al., in press). In this—as in all other such searches—there is no evidence for any signal and limits can be placed on the product branching ration, as shown in Figure 6.

The lack of any signal for a particle below 10 GeV does not rule out its existence: the result could be due to small coupling constants. However, the current results rule out large areas of NMSSM parameter space, and the limit $g_2^2 \times Br(A^0 \rightarrow f\bar{f}) > 1$, said to be “generally preferred” in the NMSSM, is effectively excluded.

### 3.3. Dark Higgsstrahlung

If the dark Higgs and the dark photon are both light, with $M_A > 2 \times M_\gamma$, then the “Higgsstrahlung” process through a virtual $A'$, $e^+e^- \rightarrow A'^+ \rightarrow A'h$, can be followed by $h \rightarrow A'A'$, as depicted in Figure 7.
This gives three $A'$ particles in the final state, each decaying to a pair of fermions, generally written $\ell^+ \ell^-$ although, if the fermion is a quark, the resulting particle is typically a pion.

$\text{BABAR}$ and Belle have searched for such events (Lees et al., 2012; Jaegle et al., 2015), reconstructing all three pairs of particles (or two pairs, with a compatible missing mass) for the $e^+ e^-, \mu^+ \mu^-, \pi^+ \pi^-$ decay possibilities (though not the $6\pi$ mode, due to large backgrounds). Results presented involve the parameter $\alpha_D$, the ‘dark coupling constant’, as well as $M_A$ and $M_h$ and are presented differently by the two experiments, as shown in Figures 8 and 9. There is no evidence for any signal, and again limits can be set on model parameters.

### 3.4. Dark Gauge Bosons

Further, non-Abelian symmetries will give rise to more (electrically neutral) gauge bosons: $W'$, $W''$, ..., which could be narrow with low mass, but that have evaded detection so far through the small size of the coupling constant.

These would be a pair produced in the reaction $e^+ e^- \rightarrow A'^* \rightarrow W' W'$, and $\text{BABAR}$ has searched for these in the leptonic decay modes $W' \rightarrow \ell^+ \ell^-$, $\ell = e, \mu$ (Aubert et al., 2009). No signal is seen and the resulting limits on $\epsilon^2 \alpha_D$ are shown in Figure 10, where, as stated earlier, $\epsilon$ is the coupling between the dark and the conventional photon and $\alpha_D$ is the coupling constant within the dark sector itself.
3.5. Long-lived dark Higgs searches

Belle also considers cases where the $A'$ or the $h'$ particles produced in dark Higgsstrahlung have long lifetimes, travelling mm/cm before decay. Such lifetimes are possible if the coupling is small enough, and the low masses mean that dark channels are not available. This requires a separate analysis as
Such long-lived decays could result in many theories, and the particles could be produced by various mechanisms. BABAR 2015 has performed an inclusive search for “V” decays, $e^+e^- \rightarrow XL$, where $L$ decays to $e^+e^-, \mu^+\mu^-, e^+\mu^-\pi^+, K^+K^-$ or $K^+\pi^-$. 

the decays are not “prompt” and do not form part of the main vertex. Results (Jaegle, 2012) are still preliminary but a final analysis is expected soon. They are shown in Figure 11.
Efficiencies vary from 47%, for 1 GeV and 3 cm c/µ, to a few per mille at large mass and large c/µ. Backgrounds are evaluated, systematic uncertainties folded in and the significance of any deviations calculated (avoiding known mass peaks, and low-mass threshold effects). There is no reportable evidence for a signal, and the results can be used to set 90% Bayesian limits on σ × BR × efficiency, as shown in Figure 12.

For any theory predicting such particles one can use these results, together with a table of experimental efficiencies, to put limits on the model parameters.

A second set of limits is obtained for events in which the remainder of the event contains a net strangeness, in a reaction which can be written as e+e− → X_sL. Limits on the product of the branching ratios are of order 10−7, depending on the mass and lifetime.

4. Outlook and conclusions
Both B factories have ceased taking data, but their enormous sample of high-quality data is still providing useful results, in areas of physics which were not considered when they were first proposed. The continuing thrust of data analysis by a new generation of postdocs and PhD students is a great success: despite the lack of “discoveries”, these measurements are playing a significant part in constraining BSM models. The experiments will welcome theorists with new ideas for objects to search for.

Although BABAR is in the past, Belle, which was shut down in 2010, will re-emerge with an upgraded detector, Belle2, and a greatly enhanced accelerator, SuperKEKB. The detector is scheduled to roll in this year, and take its first physics data in 2017. The design goal is to increase the statistics by a factor of 40—and the cynics should remember that B-factory design goals have regularly been met and exceeded. Dark matter searches, including the Higgsstrahlung analysis, will continue as an important part of the physics programme.

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Author details
Roger Barlow1
E-mail: Roger.Barlow@cern.ch
ORCID ID: http://orcid.org/0000-0002-8295-8612
1 International Institute for Accelerator Applications, The University of Huddersfield, Queensgate Campus, Huddersfield, HD1 3DH, UK.

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