A taste of LHC physics

Recent measurements of the bizarre properties of B-mesons hint at the existence of new fundamental particles. **Tim Gershon** describes how the LHCb detector at CERN's Large Hadron Collider could soon establish beyond doubt whether the effect is real

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A new era in particle physics is about to begin. As the world's most powerful particle accelerator – the Large Hadron Collider (LHC) at CERN, just outside Geneva – prepares to switch on later this year, excitement is mounting about what researchers will discover from the proton–proton collisions that will take place at the 27 km-circumference machine. Many expect new particles to be created, perhaps ending the 30-year reign of the Standard Model of particle physics. Adding to the excitement, recent results from Fermilab and the Stanford Linear Accelerator Center (SLAC) in the US, and the KEK laboratory in Japan suggest that the LHC will reap a particularly bountiful harvest.

But the LHC's first discoveries might come from an unexpected quarter: the LHCb experiment. Unlike the mammoth "general purpose" detectors ATLAS and CMS, which will search for particles, such as the Higgs boson, produced directly in the proton–proton collisions, LHCb is a smaller experiment devoted to the study of B-mesons. These particles, which comprise a bottom quark or antiquark plus one other quark with a different "flavour", only exist for about a trillionth of a second before decaying into lighter particles. But subtle quantum effects called loops, in which virtual particles are temporarily created by borrowing energy from the vacuum, can influence the behaviour of B-mesons and give researchers a handle on particles that are too heavy to be produced directly.

This technique is called flavour physics because it involves transitions between the six quark types or flavours – up, down, charm, strange, bottom and top. It has already been used to great effect, most recently at the BaBar experiment at SLAC and at the Belle experiment at KEK. For example, the existence and mass of the top quark, which is the heaviest of all the quark flavours, were successfully predicted from loop effects in B-mesons long before the particle was produced directly at Fermilab's Tevatron collider in 1995.

As measurements of loop-dominated decays become more precise, they become sensitive to even heavier particles – including those predicted by theories that go beyond the Standard Model. As such, they provide a complementary approach to discovering new particles to the direct searches with ATLAS and CMS. However, with LHCb likely to reach its peak operational performance much sooner than ATLAS and CMS, the experiment has an excellent chance of discovering the new physics first. Designed to take advantage of the enormous numbers of B-mesons that will be produced in the proton–proton collisions, LHCb could make a major discovery within the first year of data being taken.

Matter–antimatter asymmetry

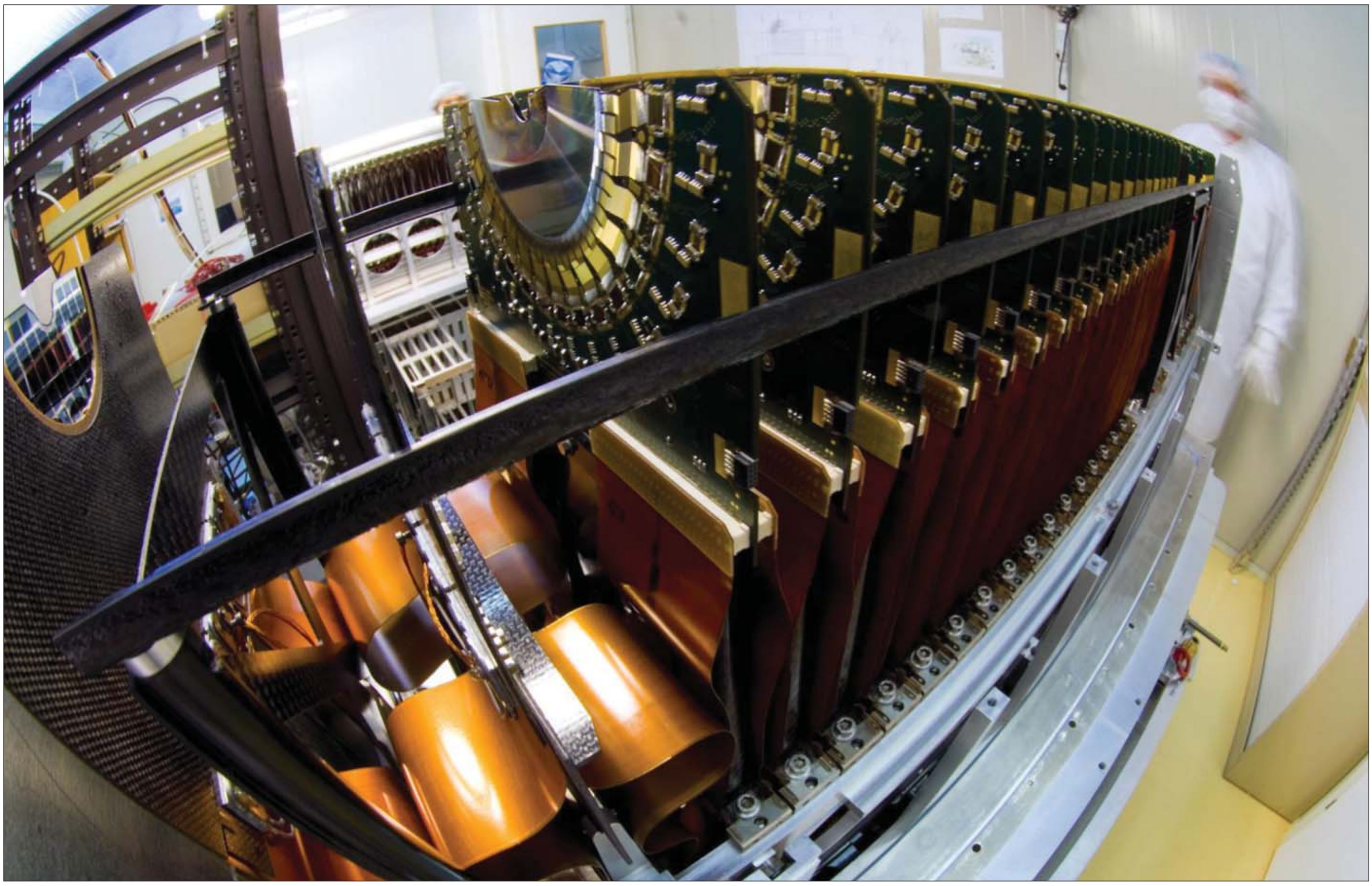
There is one very good reason to expect that new particles might appear in the quantum loops of bottom-quark decays. It is related to one of the biggest mysteries in physics: why does the universe contain more matter than antimatter? If nature treated matter and antimatter equally, then the two would have annihilated immediately after the Big Bang and produced a universe containing nothing but radiation. But since the 1960s we have found that certain processes governed by the weak interaction, which include B-meson decays, treat matter and antimatter differently.

This phenomenon is called CP violation, which is a shorthand way of saying that the laws of physics are not symmetric under the combined operations of: C (charge conjugation, whereby particles and antiparticles are interchanged) and P (parity reversal, whereby all spatial co-ordinates are reversed). The Standard Model incorporates CP violation via the Cabibbo–Kobayashi–Maskawa (CKM) "mixing" matrix, which describes the probability that a quark will change from one flavour to another when it interacts with the messenger particle of the weak force, the W-boson. Antiquarks are governed by the same matrix, but with all the entries replaced by their complex conjugates. Since some numbers in the CKM matrix have non-zero imaginary parts, quarks and antiquarks therefore have slightly different interactions.

The problem is that the amount of CP violation provided by the quarks is roughly a billion times too small to generate the observed matter–antimatter asymmetry. Nature must therefore contain as yet undiscovered heavy particles that add new sources of CP violation. This fits neatly with current theories that attempt to address some of the shortcomings of the Standard Model. For example, supersymmetry – a theory that gets round some of the shortcomings of the Standard Model by positing that each fundamental particle has a supersymmetric partner that is too heavy to have been observed so far – may have introduced new sources of CP violation into the early universe.

Alternatively, the missing contribution to CP viol-

New results suggest that the LHCb experiment has an excellent chance of finding signals of new physics in the next few years



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On target The vertex locator, or VELO, detector is part of the LHCb experiment and can measure where B-mesons created in proton–proton collisions are produced.

ation could come from neutrinos. The discovery in 1998 that neutrinos have a small mass forces us to explain why neutrinos are so much lighter than the electron, muon and tau leptons with which they are partnered. So-called Majorana models, in which the neutrino is its own antiparticle, can solve this by pairing up neutrinos with much heavier neutrinos that have not yet been observed. As with supersymmetric particles, these heavy neutrinos (which could be a source of CP violation) are expected to leave their mark through the effect of loops.

For the last five years, both the BaBar and Belle "B-factories" have seen tantalizing hints of new sources of CP violation by observing how bottom quarks decay into strange quarks. This process proceeds via "penguin" loops, so named because the Feynman diagram that represents them looks a bit like a penguin (see box on page 24). The Standard Model predicts that the amount of CP violation in these decays – such as a B^0-meson (a bottom antiquark plus a down quark) decaying into a ϕ-meson and a K_S-meson – should be the same as is seen in more direct decays, such as when a B^0-meson decays into a J/ψ (a charm–anticharm quark pair) and a K_S. The fact that the measured amount of CP violation is slightly different in the two cases suggests that there may very well be new particles beyond the Standard Model.

But despite considerable effort, it has proved frustratingly difficult to confirm whether the effects seen are really due to the presence of new particles. This is mainly because the decay modes in question are very rare, although theoretical uncertainties in the Standard Model can also conceal the subtle effects of new particles.

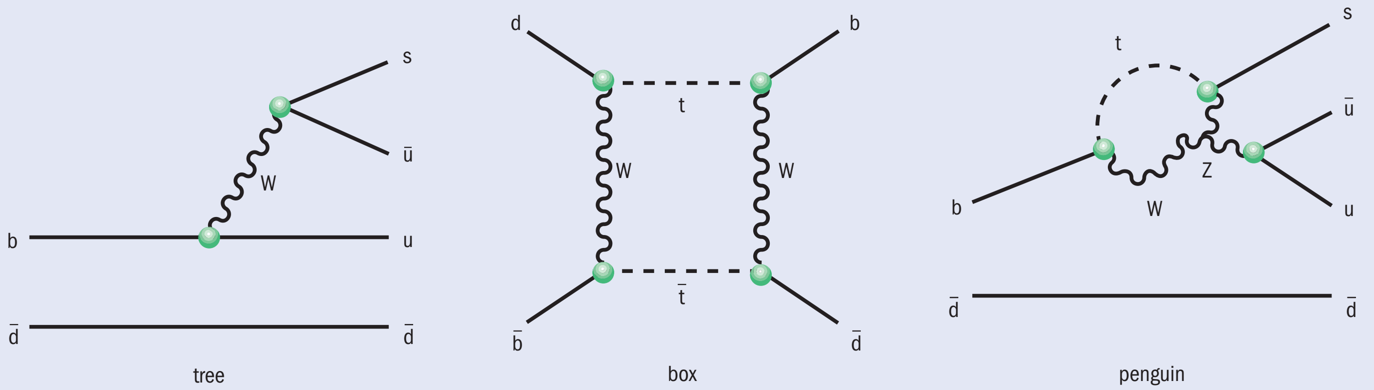
Quantum oscillations

In 2006 researchers working on the CDF experiment at Fermilab opened another avenue to search for new particles using B-mesons. It is based not on the B^0-meson but the B_s-meson, which contains a bottom antiquark and a strange quark (see *Physics World* July 2006 pp32–34). By exchanging two virtual W-bosons and two virtual top quarks – a process described by a "box-shaped" Feynman diagram – B_s-mesons can oscillate into their antimatter counterparts an astonishing three trillion times per second. While the Standard Model predicts B_s oscillations at about this rate, it also prevents CP violation effects in such processes from being larger than a few per cent. In other words, the transition of a B_s into a anti-B_s-meson should be almost exactly the same as that of an anti-B_s-meson turning into a B_s.

The observation of B_s oscillations kick-started a race to test this prediction of the Standard Model, and in the last few months both CDF at Fermilab and its partner experiment D0 found that the B_s system could indeed contain large CP-violating effects (arXiv:0712.2397 and arXiv:0802.2255).

While these results are yet to be officially combined, a preliminary analysis released at the start of March by the UTfit group (which comprises 13 experimental and theoretical physicists) claims that the probability of the CDF and D0 results being due to a statistical fluctuation is no more than 3 in 1000 (arXiv:0803.0659). If correct, this suggests there could be a new CP-violating contribution to the B_s oscillation diagram that is about as large as the Standard Model contribution. Furthermore, based on comparisons with all other measure-

Quantum loops



In a quantum field theory such as the enormously successful Standard Model of particle physics, particles do not behave like classical billiard balls but instead follow the rules of quantum mechanics. Most importantly, the uncertainty principle allows heavy "virtual" particles to be temporarily created by borrowing energy from the vacuum for very brief instants. These particles can have measurable effects on the way real particles interact or decay.

Such interactions are usually represented by Feynman diagrams, in which each particle is drawn as a line (since virtual particles only exist temporarily, their lines must both begin and end inside the diagram). These simple and convenient pictures are rigorously connected to the underlying mathematics of the Standard Model through a set of rules that allows the probabilities for each interaction to be calculated. The predictions of the Standard Model and other theories, including the role of virtual particles, can therefore be tested against experiment.

The diagram on the left shows a "tree level" decay of the $\bar{B}^0$-meson – a bottom quark and down antiquark – in which there are no loops. The bottom quark simply decays to an up quark while emitting a virtual W^--boson, which in turn decays to produce a strange quark and an up antiquark. The quarks then "hadronize" to form a pion (π^+) and a kaon (K^-).

The middle diagram shows the "box" loop that mediates B^0–$\bar{B}^0$ oscillations. Through the exchange of two virtual W-bosons and two virtual top quarks, a B^0-meson (which contains a down quark and a bottom antiquark) transforms into a $\bar{B}^0$-meson. New heavy particles could replace the top quark or the W-boson in the diagram, causing observable effects.

The third Feynman diagram is a so-called penguin diagram. Here, the bottom quark in a $\bar{B}^0$-meson emits a W-boson, as for the tree diagram, but this time produces a virtual top quark, too. After radiating a virtual Z-boson (which decays to an up and up antiquark pair), the top recombines with the W-boson to form a strange quark. The quarks hadronize to form a π^+ and a K^-. The interference between this diagram and the tree diagram can manifest itself as CP violation. New heavy particles such as those predicted by supersymmetry could replace the top quark, the W-boson or the Z-boson in the diagram, causing deviations from the Standard Model predictions.

ments to date, the new particles may be not much heavier than the top quark. This is a very exciting prospect indeed for LHC physicists as it is clearly within the reach of the accelerator.

Just a few weeks after the CDF and D0 results appeared, researchers at the Belle experiment announced a similarly striking measurement that further hints at the existence of new particles (*Nature* **452** 332). Previous results from Belle and BaBar had found CP violation in the decay of neutral B-mesons to a charged kaon and an oppositely charged pion (i.e. a difference in the probabilities for the relevant B^0 and $\bar{B}^0$ decays). The Standard Model incorporates this effect, but predicts that it should be matched by a similar effect in the corresponding decays of charged B-mesons. But the Belle team found that its result had the opposite sign to the prediction. Theorists are now trying to determine whether the discrepancy is due to uncertainties in the Standard Model or to new particles at play in the penguin loop.

These are not the only measurements that point to the existence of new particles. For several years, measurements of the anomalous magnetic moment of the muon have been at odds with the Standard Model. Given the remarkable agreement between theory and experiment for the magnetic moment of the electron, which only takes place if loop diagrams are taken into account, theorists have long suspected that new particles could reveal themselves as corrections to the muon's magnetic moment as predicted by the Standard Model.

Another possible recent sighting of new physics has been found in decays of D_s-mesons, which are made up of charm quarks and strange antiquarks. In May, researchers working on the CLEO experiment at Cornell University in the US found that the rate at which D_s-mesons decay into leptons differs significantly from the Standard Model prediction based on calculations from lattice quantum chromodynamics (arXiv:0803.0512). These results, which are supported by measurements at Belle and BaBar, suggest that an electrically charged companion to the neutral Higgs boson could be contributing to the decay (charged Higgs bosons are predicted by supersymmetry and other theories).

Furthermore, measurements of CP violation in B^0 oscillations, which are much more precise than those of B_s oscillations, also depart intriguingly from expectations. In the Standard Model, various measurable parameters in the B^0 system – such as the rate of CP violation in B^0 oscillations – define the sides and angles of a "unitary" triangle (see *Physics World* April 2007 pp24–29). To an increasing extent, the measured values of these sides and angles appear to be deviating from the triangle hypothesis, which suggests that new particles could be contributing to loops in B^0 oscillations just as they may be in B_s oscillations (arXiv:0803.4340). The much larger numbers of B-mesons that will be produced in LHCb mean that the angles of this diagram can be

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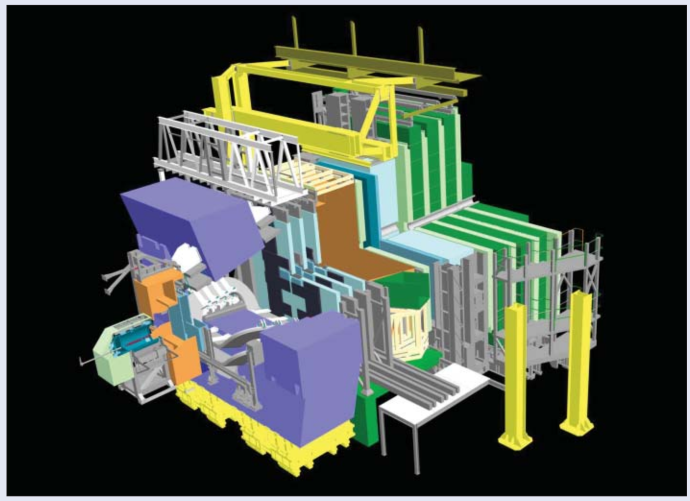
Ground to a halt
The photomultipliers on the LHCb's calorimeter will determine the energy of particles produced in collisions by measuring the ultraviolet light that they create when they slam into its plates.

Fast forward to LHCb



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The LHCb detector is one of four giant detectors positioned around the 27 km circumference LHC ring where protons will begin to collide later this year. It is designed to measure particles (hadrons) that contain bottom quarks, which at the LHC will be predominantly produced in the "forward direction" – i.e. at small angles with respect to the beams. LHCb therefore covers an angular region from close to the beam pipe to about 17°, with a series of different detectors positioned one after another to measure different aspects of the particles produced in the proton–proton collisions.

One particularly important subdetector for LHCb is the vertex locator or VELO, in which silicon wafers implanted with thousands of strips detect the passage of charged particles. The strips are just 8 mm away from the actual proton beams, thus allowing the positions where the B-mesons are produced (vertexes) to be measured very precisely. Studies of B-mesons also have to distinguish accurately between charged kaons and pions in order to identify which of many possible B-meson decay modes has been produced. At LHCb this is achieved utilizing the so-called Cerenkov radiation that is produced when a charged particle passes through a material faster than the speed of light in that substance (see *Physics World* October 2006 pp37–39).

pinned down more precisely, which will allow a thorough search for new sources of CP violation in B^0 oscillations and decays.

Global perspective

Taken together, the numerous hints from different experiments across the world strongly point to the existence of new particles. This is tantalizing indeed for researchers working on the LHC experiments. However, the measurements that have been made so far cannot tell us exactly what the masses of the new particles should be, nor what they should decay into. Consequently, the results do not provide much guidance to ATLAS and CMS researchers as to where precisely they should look, or even what exactly they should be looking for. It is a bit like searching for a needle in a haystack, only without the knowledge that the object in question is metallic and needle-shaped! Alarmingly, there remains the possibility that the new particles are just above the mass (i.e. energy) range that the LHC can explore.

In contrast, the new results suggest that the LHCb experiment has an excellent chance of finding signals of new physics in the next few years because, unlike ATLAS and CMS, it will be searching for the effects of quantum loops, rather than the direct production of new particles. The enormous quantities of B-mesons that will be produced at LHCb – thousands of times more than have been produced at SLAC and KEK – will allow researchers to study their properties with unprecedented precision. If CP violation in B_s oscillations is present at the level suggested by the CDF and D0 results, for instance, LHCb will establish the effect beyond any doubt within the first few months of operation.

The most exciting prospect is that signals of new physics will be seen at ATLAS and CMS as well as at LHCb. If this is the case, then the interplay between the measurements will allow tests of models of new physics that would not be possible with results from one experiment alone. A recent series of workshops at CERN has highlighted both the interest in and the difficulty of addressing this challenge, resulting in a series of documents totalling nearly 700 pages and authored by over 300 physicists (arXiv:0801.1800; arXiv:0801.1833 and arXiv:0801.1826).

These workshops have illustrated the need to complement measurements of quantum loops made at LHCb and at other experiments with information from a totally new facility: the proposed "super flavour factory". As well as provide a much larger number of B-mesons than BaBar (which has recently shut down) and Belle, this electron–positron collider would produce B-mesons in an environment that contains much less debris than the LHC's proton–proton collisions, thus making their decays much easier to identify and understand. A proposal for such a facility in Italy is currently in the planning stages, but if all goes well, it could be taking data by the middle of the next decade.

By combining the information on new particles from quantum loops with the direct production of those particles at the LHC, there are great hopes that our understanding of nature will undergo a paradigm shift in the next decade. If the hints from the current measurements are not a cruel tease of nature, then results from LHCb will herald the beginning of the new era sooner rather than later. ■