Physics Beyond the Standard Model

John Ellis

Theory Division, Physics Department, CERN, CH 1211 Geneva 23, Switzerland

Abstract

The Standard Model is in good shape, apart possibly from $g_\mu - 2$ and some niggling doubts about the electroweak data. Something like a Higgs boson is required to provide particle masses, but theorists are actively considering alternatives. The problems of flavour, unification and quantum gravity will require physics beyond the Standard Model, and astrophysics and cosmology also provide reasons to expect physics beyond the Standard Model, in particular to provide the dark matter and explain the origin of the matter in the Universe. Personally, I find supersymmetry to be the most attractive option for new physics at the TeV scale. The LHC should establish the origin of particle masses has good prospects for discovering dark matter, and might also cast light on unification and even quantum gravity. Important roles may also be played by lower-energy experiments, astrophysics and cosmology in the searches for new physics beyond the Standard Model.

CERN-PH-TH/2008-020

1. Status of the Standard Model

The Standard Model is in perfect agreement with all confirmed collider data, but requires a missing ingredient: the Higgs boson or something to replace it in giving masses to the elementary particles. As well as old theoretical arguments on high-energy behaviour [1], the consistency of the Standard Model with the precision electroweak data from LEP, the Tevatron, etc. not only requires something resembling a Higgs boson, but seems to suggest that it or its replacement physics should be relatively light, as discussed below.

We learnt in high school that Newton had discovered that weight is proportional to mass, and Einstein taught us that energy is related to mass by the infamous equation $E = mc^2$. However, neither of these distinguished gentlemen remembered to explain the origin of mass itself. The answer may be provided by Brout, Englert [2] and Higgs [3],

who postulated a ubiquitous, universal and constant background field (think a flat desert plain). As Higgs pointed out, this field would have an associated quantum particle (think grain of sand), that we call the Higgs boson, which has now become the Holy Grail of particle physicists. (Related ideas, applied to the strong interactions, won half the 2008 Nobel Physics Prize for Nambu [4].)

The precision electroweak data by themselves indicate that $m_h = 86^{+36}_{-24}$ GeV [5], whereas LEP imposes $m_h > 114.4$ GeV [6], and the Tevatron collider excludes a Higgs boson weighing 170 GeV [7]. Combining all the available information, the Gfitter group finds [8]

$$m_h = 116.4^{+18.3}_{-\ 1.3} \text{ GeV}, \tag{1}$$

and quotes the ranges (114, 145) GeV at the 68% confidence level and (113, 168) and (180, 225) GeV at the 95% confidence level [8]. The Higgs search is the centrepiece of LHC physics, but will the LHC hare be beaten by the Tevatron tortoise? This is possible if m_h is close to the value 170 GeV already excluded, but seems unlikely if $m_h \sim 115$ to 120 GeV, which is favoured (1) by the precision electroweak data and independently by supersymmetry (of which more later).

There is one piece of accelerator data that may disagree with the Standard Model, namely the measurement of the anomalous magnetic moment of the muon, $g_\mu - 2$ [9]. The Standard Model prediction calculated using older low-energy e^+e^- data disagrees with the BNL measurement by over 3 σ [10]. However, the value calculated using τ decay data disagrees with the BNL value by barely 1 σ, and the preliminary result of a new analysis of e^+e^- data from BABAR lies in between [11]. Hence it remains unclear whether there is indeed a significant disagreement with the Standard Model.

2. Open Questions beyond the Standard Model

The *origin of particle masses*, and whether they are due to a Higgs boson, is only one of the open questions beyond the Standard Model. Another important set of issues bears on the questions *why there are so many different types of matter particles*, and why the quark and neutrino flavours mix in the way they do. A related question is *the origin of CP violation*, which is described within the quark sector of the Standard Model by the Kobayashi-Maskawa [12] model, but not really explained. Also, is there some CP violation beyond the Standard Model that may explain the dominance of matter over antimatter in the Universe today? Another prominent cosmological question is *the nature of the dark matter* that constitutes some 80% of the matter in the Universe [13]. There is no Standard Model candidate for the dark matter, but there are good arguments that it might appear at the TeV scale [14]. Returning to straight particle physics, there is the question *whether the fundamental forces may be unified*. If a unified theory is to include gravity, it must also answer the question *how to construct a consistent quantum theory of gravity*, a question whose answer has eluded physicists ever since general relativity and Quantum Mechanics were formulated almost a century ago.

The good news is that many of these questions will be addressed, if not completely answered, by the LHC. It should discover the Higgs boson, or whatever other physics replaces it at the TeV scale, which is also the scale at which many dark matter candidates should appear. If new particles are found at this scale, they will accentuate the flavour

problem and be essential ingredients that may indicate how to unify the fundamental interactions. Remarkably, some unification scenarios that invoke additional dimensions of space predict that gravity should become strong at the TeV scale, in which case the LHC will be a fantastic place to study quantum effects of gravity.

3. Supersymmetry

I make no bones about the fact that I regard supersymmetry as the most plausible extension of the Standard Model, for many different reasons. It is beautiful, and apparently an essential ingredient in string theory, the most-favoured candidate for unifying all the particle interactions including gravity. All well and fine, but there are, moreover, many reasons for thinking that supersymmetry might appear at the TeV scale, and hence be accessible to the LHC.

It would help stabilize the hierarchy of mass scales in physics between m_W and the grand unification scale or the Planck mass, by cancelling the quadratic divergences in the radiative corrections to the mass-squared of the Higgs boson [15], and by extension to the masses of other Standard Model particles. This motivation suggests that sparticles weigh less than about 1 TeV, but the exact mass scale depends on the amount of fine-tuning that one is prepared to tolerate [16].

Historically, the second motivation for low-scale supersymmetry was the observation that the lightest supersymmetric particle (LSP) in models with conserved R parity, being heavy and naturally neutral and stable, would be an excellent candidate for dark matter [17,18]. This motivation requires that the lightest supersymmetric particle should weigh less than about 1 TeV, if it had once been in thermal equilibrium in the early Universe [14]. This would have been the case for a neutralino χ (mixture of the supersymmetric partners of the Z, γ and neutral Higgs bosons) or a sneutrino $\tilde{\nu}$ LSP, and the argument can be extended to a gravitino LSP because it may be produced in the decays of heavier, equilibrated sparticles.

The third reason that emerged for thinking that supersymmetry may be accessible to experiment was the observation that including sparticles in the renormalization-group equations (RGEs) for the gauge couplings of the Standard Model would permit them to unify [19], whereas unification would not occur if only the Standard Model particles were included in the RGEs. However, this argument does not constrain the supersymmetric mass scale very precisely: scales up to about 10 TeV or perhaps more could be compatible with grand unification.

The fourth motivation is the fact that the Higgs boson is (presumably) relatively light, as mentioned earlier. It has been known for some 20 years that the lightest supersymmetric Higgs boson should weigh no more than about 140 GeV, at least in simple models [20], in perfect agreement with the indications from precision electroweak data and the unsuccessful searches at LEP and the Tevatron collider.

Fifthly, if the Higgs boson is indeed so light, the present electroweak vacuum would be destabilized by radiative corrections due to the top quark, unless the Standard Model is supplemented by additional scalar particles [21]. This would be automatic in supersymmetry, and one can extend the argument to 'prove' that any mechanism to stabilize the electroweak vacuum must look very much like supersymmetry.

A sixth argument would be provided by the anomalous magnetic moment of the muon,

$g_\mu - 2$, if we could convince ourselves that the discrepancy between the data and the Standard Model calculation based on low-energy e^+e^- data is real. Contributions to $g_\mu - 2$ from supersymmetric particles would be very capable of explaining any such discrepancy.

Fig. 1 shows the impacts of various constraints on supersymmetry, assuming that the soft supersymmetry-breaking contributions $m_{1/2}, m_0$ to the different scalars and gauginos are each universal at the GUT scale (the scenario called the CMSSM), and that the lightest sparticle is the lightest neutralino χ [22]. We see that narrow strips of the $(m_{1/2}, m_0)$ planes are compatible with all the constraints, including the astrophysical cold dark matter density, and that they vary with $\tan\beta$, the ratio of supersymmetric Higgs vacuum expectation values.
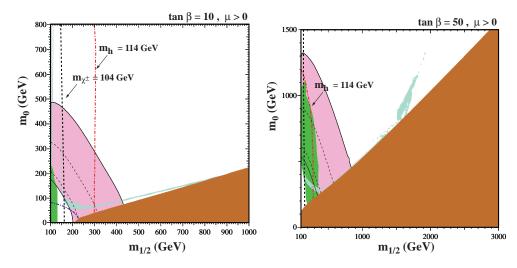

Fig. 1. *The CMSSM $(m_{1/2}, m_0)$ planes for (a) $\tan\beta = 10$ and (b) $\tan\beta = 50$, assuming $\mu > 0$, $A_0 = 0$, $m_t = 175$ GeV and $m_b(m_b)^{\overline{MS}}_{SM} = 4.25$ GeV [22]. The near-vertical (red) dot-dashed lines are the contours for $m_h = 114$ GeV, and the near-vertical (black) dashed line is the contour $m_{\chi^\pm} = 104$ GeV. Also shown by the dot-dashed curve in the lower left is the region excluded by the LEP bound $m_{\tilde{e}} > 99$ GeV. The medium (dark green) shaded region is excluded by $b \to s\gamma$, and the light (turquoise) shaded area is the cosmologically preferred region. In the dark (brick red) shaded region, the LSP is the charged $\tilde{\tau}_1$. The region allowed by the measurement of $g_\mu - 2$ at the 2-σ level assuming the e^+e^- calculation of the Standard Model contribution, is shaded (pink) and bounded by solid black lines, with dashed lines indicating the 1-σ ranges.*

4. Where is the Physics Beyond the Standard Model?

As we have seen, there are many reasons to expect some new physics at the TeV scale, which should be accessible to the LHC. These include the Higgs boson and whatever physics (such as supersymmetry) stabilizes the Higgs mass and hence the electroweak scale. There are also general arguments that many weakly-interacting particle candidates for dark matter should also weigh a TeV or less. There is also an abundance of lower-energy experiments that may be sensitive indirectly to TeV-scale physics.

On the other hand, there are several examples of new physics that may well lie beyond the LHC's reach. One example is the mechanism responsible for neutrino masses, which

probably lies far beyond the TeV scale, and another is grand unification, which is thought to occur at a scale $\sim 10^{16}$ GeV. If one wishes to probe quantum gravity, one may need to reach the Planck mass $\sim 10^{19}$ GeV, at which gravity in four dimensions would acquire strength equal to the other particle interactions. Physics at these scales could only be explored indirectly by the LHC and other low-energy experiments. On the other hand, grand unification might occur at some lower energy scale, and gravity might become strong at much lower energies, if there are additional dimensions of space. There is, to my mind, no compelling reason to think that extra-dimensional physics should appear at the LHC, but some possibilities are discussed later in this talk.

Some of the high-scale physics may be accessible only via astrophysics and cosmology, e.g., via high-energy astrophysical sources, measurements of the cosmological microwave background radiation, or the detection of gravitational waves. Thus, although the LHC has bright prospects for detecting new physics, it does not have a monopoly!

5. The LHC Haystack

The total cross section for proton-proton collisions at the LHC is $\sim \mathcal{O}(1/(100\text{MeV})^2)$, whereas cross sections for producing heavy particles weighing $\sim N$ TeV are typically $\sim \mathcal{O}(1/(N \text{ TeV})^2)$. Moreover, many of the cross sections for producing new particles have small coupling factors $\mathcal{O}(\alpha^2)$, and so are expected to be produced at rates $\sim 10^{-12}$ of the total cross section or even less. To add insult to injury, many of the new physics signals have significant backgrounds, and may require as many as 1000 events to be confirmed. Discovering them at the LHC will be rather like looking for a needle in $\sim$ 100000 haystacks! Hence, big LHC discoveries will not occur on the first day of high-energy collisions, but will require the patient accumulation of integrated luminosity and good understanding of the detectors.

As seen in Fig. 2, the LHC may start being able to *exclude* certain ranges for the mass of the Higgs boson with a fraction of an inverse femtobarn of well-understood luminosity. However, the 5-σ discovery of a Standard-Model-like Higgs boson, whatever its mass, will surely require several inverse femtobarns.

6. Theorists are getting Cold Feet

The threat that the Higgs boson may soon be discovered, finally, has concentrated wonderfully the minds of theorists. They are busy concocting excuses in case it is not discovered, by finding reasons why the LHC may not discover a Standard-Model-like Higgs boson.

Some are considering composite Higgs models, and grappling with potential conflicts with the precision electroweak data [23]. Others question the standard interpretation of the electroweak data, and wondering whether the Higgs boson might be very heavy and hence difficult to detect [24]. Others accept the electroweak data at face value, but suggest that higher-dimensional interactions involving Standard model particles might play an essential role in the fits, in which case the Higgs boson could again be uncomfortably heavy [25]. Yet others consider Higgsless models, in which WW scattering becomes strong at high energies [26]. This would also create problems with the precision electroweak data, that may be alleviated by postulating extra spatial dimensions.
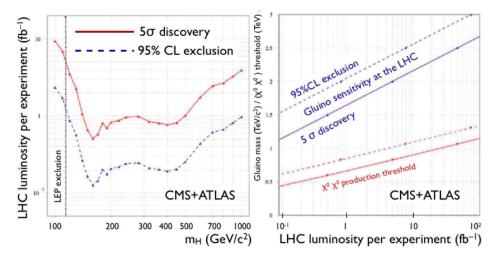
Fig. 2. *The amounts of integrated LHC luminosity at $E_{CM} = 14$ TeV required (left) either to exclude a Standard Model Higgs boson at the 95% confidence level (blue line) or discover it at the 5-σ level (red line), and (right) either to exclude a gluino (blue dashed line) or discover it (blue solid line). The corresponding thresholds for χ pair production in e^+e^- are shown in red [30].*

The primary question concerning the precision electroweak data is whether they all tell the same story, because there are at least two discrepancies worth noting [24]. One is between the measurements of leptonic and hadronic asymmetries $A_{L,H}$ in Z decays: relatively low values of m_h are favoured by A_L (and m_W), but larger values would be preferred by measurements of A_H. Another discrepancy is between the NuTeV determination of $\sin^2 \theta_W$ [27] and the value preferred by LEP. Most of us think that these are statistical or systematic artefacts (the NuTeV measurement, in particular, is fraught with hadronic uncertainties), and lump all the data together. On the other hand, perhaps one or the other of these discrepancies is due to some new physics, in which case one cannot use the precision electroweak data to estimate m_h within a naive Standard Model framework [24].

If, despite these questions, one accepts the electroweak data at face value, and the Higgs boson is relatively light, are there any alternatives to the Standard Model or its supersymmetric extension? One interesting possibility is offered by 'Little Higgs' models, in which the Standard-Model-like Higgs boson is a pseudo-Goldstone boson in some model that reveals compositeness at the multi-TeV scale [28]. Such models necessarily predict the existence of additional particles below this compositeness scale, such as an extra top-like quark, gauge bosons, and Higgs-like scalars. Lots of exciting stuff for the LHC and other colliders to look for! Remarkably, one-loop diagrams involving these particles exhibit cancellations of quadratic divergences, analogous to those in supersymmetric theories. However, these cancellations do not continue in higher orders, unlike the case of supersymmetry, where these divergences occur in all orders of perturbation theory. This is one of the many reasons why I, personally, prefer supersymmetry, so let us now cut to the chase.

6

7. Searches for Supersymmetry

As discussed earlier, in the minimal supersymmetric extension of the Standard Model (MSSM), supersymmetric particles carry a multiplicatively-conserved quantum number R, implying that sparticles must be produced in pairs, that heavier sparticles must decay into lighter ones, and that the lightest sparticle (LSP) must be stable, since it has no legal decay mode. The LSP is the supersymmetric candidate for the astrophysical cold dark matter, and should presumably have neither electric charge nor strong interactions - otherwise, it would bind to regular matter and form anomalous heavy nuclei that have never been observed [18]. It is the weakly-interacting nature of the LSP that provides the classic supersymmetric signature of missing (transverse) energy carried away by dark matter particles, e.g., the lightest neutralino χ.

Simulations for the LHC experiments ATLAS and CMS indicate that this missing-energy signature should be detectable if the squarks and gluinos weigh up to about 2.5 TeV [29]. Assuming that the supersymmetry-breaking gaugino masses $m_{1/2}$ are universal at the GUT scale, as in the CMSSM, this would correspond to a mass of about 400 GeV for the neutralino χ. The threshold for producing pairs of supersymmetric particles must be at least as large as $2m_\chi$. Hence discovering (excluding) gluinos at (up to) some mass would provide a lower limit for producing sparticles in e^+e^- annihilation, as seen in the right panel of Fig. 2 [30]. The results of LHC searches for supersymmetry will tell e^+e^- colliders where (not) to look!

How soon might the CMSSM be detected at the LHC? Fig. 3 shows the results of a likelihood analysis [31] of the constraints, crucially including $g_\mu - 2$, assuming that there is a significant discrepancy between the experimental measurement and the Standard Model prediction as indicated by low-energy e^+e^- data [10]. The black dot indicates the best-fit point in the $(m_{1/2}, m_0)$ plane, the blue-hatched region is that favoured at the 68% C.L., and the red-hatched region is that favoured at the 95% C.L. Also shown are the regions of the CMSSM $(m_0, m_{1/2})$ plane where the LHC could discover supersymmetry with the indicated amounts of luminosity at the indicated energies. We see that the best-fit point would be accessible already with 50/nb at $E_{CM} = 10$ TeV, and (almost) all the 95% C.L. region could be explored with 1/fb at $E_{CM} = 14$ TeV [31].

The left panel of Fig. 4 displays the CMSSM spectrum at the best-fit point [31]. We see that some sparticles would be accessible to a linear collider with $E_{CM} = 500$ GeV, and considerably more with $E_{CM} = 1$ TeV, and that the full spectrum could be covered with $E_{CM} = 3$ TeV. The right panel of Fig. 4 shows the correlation between the mass of the lightest neutralino χ and that of the gluino $\tilde{g}$. They are directly related via the gaugino-mass universality assumption of the CMSSM, and the other sparticle masses are also highly correlated with m_χ. The likelihood function is quite asymmetric, being cut off sharply at low masses, mainly by the LEP lower limit on m_h, and more gradually at high masses, essentially by $g_\mu - 2$. If the $g_\mu - 2$ constraint were weakened, the likelihood function would rise even more gradually at large masses, and an infinite mass, i.e., no observable supersymmetry, could not be excluded.

There are various ways to search for astrophysical dark matter, including searches for antiprotons, antideuterons or positrons in the cosmic rays that are produced by LSP annihilations in the galactic halo, γ rays from annihilations at the centre of the galaxy, and neutrinos from annihilations in the centres of the Sum or Earth. There are extant claims
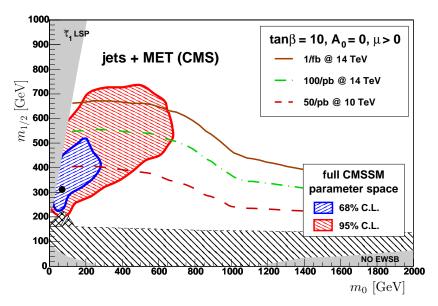
Fig. 3. *The $(m_0, m_{1/2})$ plane for the CMSSM [31], displaying the best-fit point (black dot), the 68% C.L. region (blue hatching), the 95% C.L. region (red hatching) and the region excluded by LEP and Tevatron searches (black hatching). Also shown are the 5-σ supersymmetry discovery reaches at the LHC assuming 50/pb of data at 10 TeV, 100/pb at 14 TeV, and 1/fb at 14 TeV, as estimated for the indicated values of the supersymmetric model parameters.*
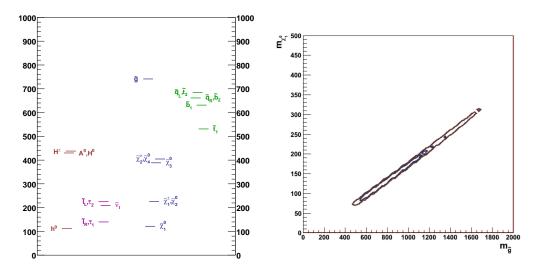

Fig. 4. *Left: The supersymmetric spectrum at the best-fit point in the CMSSM. Right: the correlation between the masses of the lightest neutralino χ and the gluino $\tilde{g}$ in the CMSSM [31].*

to have observed an excess of positrons and γ rays, but I do not find them convincing. There are fewer uncertainties in the direct searches for dark matter scattering on nuclei deep underground [32], and these might provide the toughest competition for the LHC in the search for supersymmetry.

8. CP Violation beyond the Standard Model

Dirac predicted the existence of antimatter particles with the same masses as conventional particles, but opposite internal properties such as electric charges. Antiparticles were duly discovered in cosmic rays and studied using accelerators, and it came as a complete surprise that matter and antimatter are not quite equal and opposite, at least as far as their weak interactions are concerned. This CP violation can be described within the Standard Model by the mechanism of Kobayashi and Maskawa [12], who won the other half of the 2008 Nobel Physics Prize. However, some additional matter-antimatter difference would be needed to explain why the Universe contains mainly matter, not antimatter. Could this be provided by supersymmetry?

The flavour violation and CP violation seen experimentally are so well described by the Standard Model, that one normally assumes minimal flavour violation (MFV) in the supersymmetric sector, with all squark mixing due to the Cabibbo-Kobayashi-Maskawa matrix matrix. One therefore assumes that the soft supersymmetry-breaking scalar masses are universal at the GUT (or some other high) scale for sparticles with same quantum numbers, but universality of the gaugino masses or between scalars having different internal quantum numbers is not essential. The MFV model therefore has the following parameters:

$$M_{1,2,3}; \ \ m^2_{Q,U,D,L,E}, m^2_{H_{1,2}}, \ \ A_{u,d,e}, \tag{2}$$

where $Q, U, D, L, E, H_{1,2}$ denote the supermultiplets of the doublet quarks, singlet quarks, doublet leptons, singlet leptons and Higgses, respectively, and the A_i are soft trilinear supersymmetry-breaking parameters. The maximally CP-violating MFV (MCPMFV) model has 19 parameters, of which 6 violate CP, namely the phases of $M_{1,2,3}$ and of $A_{u,d,e}$ [33]. It is often assumed that the $ImM_{1,2,3}$ and the $ImA_{u,d,e}$ are universal, but their non-universality would also be compatible with MFV.

The allowed regions of supersymmetric parameter space vary with the values of the different CP-violating phases in the MCPMFV, which affect, e.g., B_s mixing, $B_u \to \tau\nu$ decay and the rate and CP-violating asymmetry (A_{CP}) in $b \to s\gamma$. We have found sample values of the phases which give values of A_{CP} that are considerably larger than in the Standard Model, while maintaining consistency with the other B-physics observables [33], as seen in Fig. 5.

What of the prospects for supersymmetric baryogenesis at the electroweak scale? The good news is that the electroweak phase transition could be first order if one of the stop squarks is sufficiently light, and the phases in the MCPMFV model could in principle provide enough CP violation. However, both the Higgs and stop masses would be tightly constrained by the requirement of successful baryogenesis: the available window may soon be explored by either the Tevatron collider or the LHC [34].

The parameter space of the MCPMHV model is also tightly constrained by the experimental upper limits on the Thallium, Mercury and neutron electric dipole moments (EDMs). However, these three constraints cannot force all six MCPMFV phases to be small, since there are possibilities for non-trivial cancellations between the contributions of different phases [35].
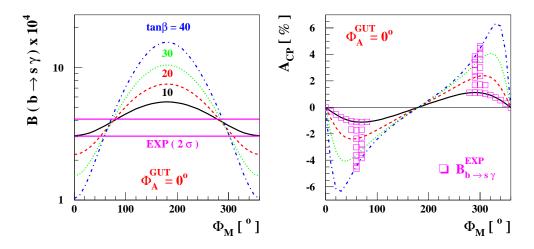
Fig. 5. *The branching ratio $B(B \to X_s\gamma)$ (left) and the CP asymmetry A_{CP} (right) as functions of a common gaugino mass phase Φ_M for four values of $\tan\beta$, taking the trilinear coupling phase $\Phi_A = 0$. The region allowed experimentally at the 2-σ level is bounded by two horizontal lines in the left frame. In the right frame, points satisfying this constraint are denoted by open squares: see [33] for details.*

9. Unification and Large Extra Dimensions?

Unification of all the fundamental interactions was Einstein's dream, but he never succeeded. One of the ideas he played with was the existence of extra spatial dimensions, and these play a key role in string theory. However, as in the case of supersymmetry, string theory does not (yet) give any clear indications on the scales of any extra dimensions. It used to be thought that they should necessarily be very small, or order the Planck length $\sim 10^{-33}$ cm, but this is not necessarily the case.

How large could extra dimensions be? If they were an inverse TeV in size, they could break electroweak symmetry (putting the Higgs boson out of a job) or supersymmetry [36]. If they were micron-size, they would enable the electroweak hierarchy problem to be rewritten [37]. There are even some 'warped' scenarios in which there is an extra dimension of infinite size [38]: in this case, we are literally the 'scum of the Universe', rather like insects skating on the surface of a pond, supported by surface tension.

These extra-dimensional scenarios have various possible experimental signatures at the LHC. Perhaps energy will be lost as it escapes into the extra dimensions via multiple graviton emission? Perhaps the LHC will discover Kaluza-Klein excitations of Standard Model particles, whose wave functions are wrapped around the extra dimensions? Perhaps gravity will become strong at the TeV scale, in which case some parton-parton collisions might produce microscopic black holes [39]?

These microscopic black holes are generally expected to be very unstable, decaying quickly into jets, leptons and photons via Hawking radiation. However, there are some speculative scenarios in which the black holes might be longer-lived [40] or even stable: these would be very interesting, but do not panic, because they would be totally

10

harmless [41]! The Earth and other astrophysical bodies have survived being subjected to collisions by cosmic rays with much higher effective energies than the LHC collisions, and we are still here.

10. Conclusions

There are many good theoretical and astrophysical reasons to expect physics beyond the Standard Model. The main raison d'être of the LHC is to look for such new physics, and it is the tool of choice for searches for the Higgs boson, supersymmetry and extra dimensions. However, many other experiments also have key roles to play, e.g., searches for EDMs, B factories, the Tevatron collider, searches of dark matter, high-energy astrophysics and cosmology. Only time will tell who discovers first which evidence for physics beyond the Standard Model!

References

[1] C. H. Llewellyn Smith, Phys. Lett. B **46** (1973) 233; J. S. Bell, Nucl. Phys. B **60** (1973) 427; D. A. Dicus and V. S. Mathur, Phys. Rev. D **7** (1973) 3111; J. M. Cornwall, D. N. Levin and G. Tiktopoulos, Phys. Rev. Lett. **30** (1973) 1268 [Erratum-ibid. **31** (1973) 572] and Phys. Rev. D **10** (1974) 1145 [Erratum-ibid. D **11** (1975) 972].
[2] F. Englert and R. Brout, Phys. Rev. Lett. **13** (1964) 321;
[3] P. W. Higgs, Phys. Lett. **12** (1964) 132; P. W. Higgs, Phys. Rev. Lett. **13** (1964) 508.
[4] Y. Nambu and G. Jona-Lasinio, Phys. Rev. **122** (1961) 345.
[5] LEP Electroweak Working Group, `http://lepewwg.web.cern.ch/LEPEWWG/`; Tevatron Electroweak Working group, `http://tevewwg.fnal.gov/`.
[6] R. Barate *et al.* [ALEPH, DELPHI, L3, OPAL Collaborations and LEP Working Group for Higgs boson searches], Phys. Lett. B **565** (2003) 61 [arXiv:hep-ex/0306033]; S. Schael *et al.* [ALEPH, DELPHI, L3, OPAL Collaborations and LEP Working Group for Higgs boson searches], Eur. Phys. J. C **47** (2006) 547 [arXiv:hep-ex/0602042].
[7] Tevatron New Phenomena and Higgs Working Group, combining CDF and D0 upper limits, `http://tevnphwg.fnal.gov/results/SM_Higgs_Summer_08/`.
[8] H. Flaecher, M. Goebel, J. Haller, A. Hoecker, K. Moenig and J. Stelzer, arXiv:0811.0009 [hep-ph].
[9] G. W. Bennett *et al.* [Muon G-2 Collaboration], Phys. Rev. D **73** (2006) 072003 [arXiv:hep-ex/0602035].
[10] M. Passera, W. J. Marciano and A. Sirlin, Phys. Rev. D **78**, 013009 (2008) [arXiv:0804.1142 [hep-ph]].
[11] M. Davier, `http://tau08.inp.nsk.su/prog.php`.
[12] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49** (1973) 652.
[13] N. A. Bahcall, J. P. Ostriker, S. Perlmutter and P. J. Steinhardt, Science **284** (1999) 1481 [arXiv:astro-ph/9906463].
[14] S. Dimopoulos, Phys. Lett. B **246** (1990) 347.
[15] L. Maiani, *All You Need To Know About The Higgs Boson*, Proceedings of the Gif-sur-Yvette Summer School On Particle Physics, 1979, pp.1-52; G. 't Hooft, in *Recent Developments in Gauge Theories*, Proceedings of the NATO Advanced Study Institute, Cargèse, 1979, eds. G. 't Hooft et al. (Plenum Press, NY, 1980); E. Witten, Phys. Lett. B **105** (1981) 267.
[16] J. R. Ellis, K. A. Olive and Y. Santoso, New J. Phys. **4** (2002) 32 [arXiv:hep-ph/0202110].
[17] H. Goldberg, Phys. Rev. Lett. **50** (1983) 1419.
[18] J. R. Ellis, J. S. Hagelin, D. V. Nanopoulos, K. A. Olive and M. Srednicki, Nucl. Phys. B **238** (1984) 453.

[19] J. R. Ellis, S. Kelley and D. V. Nanopoulos, Phys. Lett. B **249** (1990) 441 and Phys. Lett. B **260** (1991) 131; U. Amaldi, W. de Boer and H. Furstenau, Phys. Lett. B **260** (1991) 447; C. Giunti, C. W. Kim and U. W. Lee, Mod. Phys. Lett. A **6** (1991) 1745; P. Langacker and M. x. Luo, Phys. Rev. D **44** (1991) 817.

[20] J.R. Ellis, G. Ridolfi and F. Zwirner, Phys. Lett. B **257** (1991) 83 and B **262** (1991) 477: Y. Okada, M. Yamaguchi and T. Yanagida, Prog. Theor. Phys. **85** (1991) 1 and Phys. Lett. B **262** (1991) 54; H.E. Haber and R. Hempfling, Phys. Rev. Lett. **66** (1991) 1815.

[21] J. R. Ellis and D. Ross, Phys. Lett. B **506** (2001) 331 [arXiv:hep-ph/0012067].

[22] These figures are updated versions of those in J. R. Ellis, K. A. Olive, Y. Santoso and V. C. Spanos, Phys. Lett. B **565** (2003) 176 [arXiv:hep-ph/0303043].

[23] E. Eichten and K. Lane, Phys. Lett. B **669** (2008) 235 [arXiv:0706.2339 [hep-ph]].

[24] M. S. Chanowitz, Phys. Rev. D **66** (2002) 073002 [arXiv:hep-ph/0207123].

[25] R. Barbieri and A. Strumia, arXiv:hep-ph/0007265.

[26] C. Csaki, C. Grojean, L. Pilo and J. Terning, Phys. Rev. Lett. **92** (2004) 101802 [arXiv:hep-ph/0308038].

[27] G. P. Zeller *et al.* [NuTeV Collaboration], Phys. Rev. Lett. **88** (2002) 091802 [Erratum-ibid. **90** (2003) 239902] [arXiv:hep-ex/0110059].

[28] M. Schmaltz and D. Tucker-Smith, Ann. Rev. Nucl. Part. Sci. **55** (2005) 229 [arXiv:hep-ph/0502182].

[29] G. Aad *et al.* [ATLAS Collaboration], arXiv:0901.0512; G. L. Bayatian *et al.* [CMS Collaboration], *CMS Technical Design Report, Volume II: Physics Performance*, CERN-LHCC-2006-021, CMS-TDR-008-2 J. Phys. G34, 995 (2007); see: `http://cmsdoc.cern.ch/cms/cpt/tdr/`.

[30] A. Blondel, L. Camilleri, A. Ceccucci, J. R. Ellis, M. Lindroos, M. Mangano and G. Rolandi, arXiv:hep-ph/0609102; J. R. Ellis, K. A. Olive and P. Sandick, JHEP **0808** (2008) 013 [arXiv:0801.1651 [hep-ph]].

[31] O. Buchmueller *et al.*, JHEP **0809** (2008) 117 [arXiv:0808.4128 [hep-ph]].

[32] However, even in this case the uncertainties are not negligible; see J. R. Ellis, K. A. Olive and C. Savage, Phys. Rev. D **77** (2008) 065026 [arXiv:0801.3656 [hep-ph]].

[33] J. R. Ellis, J. S. Lee and A. Pilaftsis, Phys. Rev. D **76** (2007) 115011 [arXiv:0708.2079 [hep-ph]].

[34] See M. Carena, G. Nardini, M. Quiros and C. E. M. Wagner, arXiv:0809.3760 [hep-ph] and references therein.

[35] J. R. Ellis, J. S. Lee and A. Pilaftsis, JHEP **0810** (2008) 049 [arXiv:0808.1819 [hep-ph]].

[36] I. Antoniadis, Phys. Lett. B **246** (1990) 377.

[37] I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B **436** (1998) 257 [arXiv:hep-ph/9804398].

[38] L. Randall and R. Sundrum, Phys. Rev. Lett. **83** (1999) 3370 [arXiv:hep-ph/9905221].

[39] S. B. Giddings and S. D. Thomas, Phys. Rev. D **65** (2002) 056010 [arXiv:hep-ph/0106219]; S. Dimopoulos and G. L. Landsberg, Phys. Rev. Lett. **87** (2001) 161602 [arXiv:hep-ph/0106295].

[40] See R. Casadio, S. Fabi and B. Harms, arXiv:0901.2948 [hep-ph] and references therein.

[41] S. B. Giddings and M. L. Mangano, Phys. Rev. D **78** (2008) 035009 [arXiv:0806.3381 [hep-ph]]; J. R. Ellis, G. Giudice, M. L. Mangano, I. Tkachev and U. Wiedemann, J. Phys. G **35** (2008) 115004 [arXiv:0806.3414 [hep-ph]]; S. B. Giddings and M. L. Mangano, arXiv:0808.4087 [hep-ph].