Gauguin's questions in particle physics:

Where are we coming from? What are we? Where are we going?

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Abstract.
   Within particle physics itself, Gauguin's questions may be interpreted as:
P1 - What is the status of the Standard Model?
P2 - What physics may lie beyond the Standard Model?
P3 - What is the 'Theory of Everything'?
Gauguin's questions may also asked within a cosmological context:
C1 - What were the early stages of the Big Bang?
C2 - What is the material content of the Universe today?
C3 - What is the future of the Universe?
In this talk I preview many of the topics to be discussed in the plenary sessions of this conference, highlighting how they bear on these fundamental questions.

1. Prologue

As a research student, I stuck a copy of the Gauguin painting shown in Fig. 1 on the wall of my office, just to remind me why I was there. When the organizers asked me to give an 'inspirational' opening talk here, I opted to use Gauguin's questions to structure it. In the following, I introduce many of the 'Big Issues' in particle physics and cosmology, discussing them in relation to the questions raised by Gauguin.

2. What is the Status of the Standard Model? (P1)

2.1. Flavour and CP Violation

One of the most impressive developments in particle physics over the past few years has been the continued success of the Kobayashi-Maskawa (KM) model of flavour and CP violation within the Standard Model [1], worthily recognized by this year's EPS Prize for High-Energy and Particle Physics. The torrent of data from the B factories and elsewhere, including the Tevatron and fixed-target experiments [2], has been largely in agreement with the KM model, as shown in the left panel of Fig. 2 [3]. There are no significant discrepancies at present, though there some instances, e.g., $b \to s$ penguin processes, where the data do not (yet) agree perfectly with the KM model. It is now clear that the KM model explains most of the flavour and CP violation seen experimentally, and the question is rather whether it needs to be supplemented by any additional flavour physics beyond the KM model [4]. KM is now the third pillar of the Standard Model, joining QCD [5] and precision electroweak physics [6].
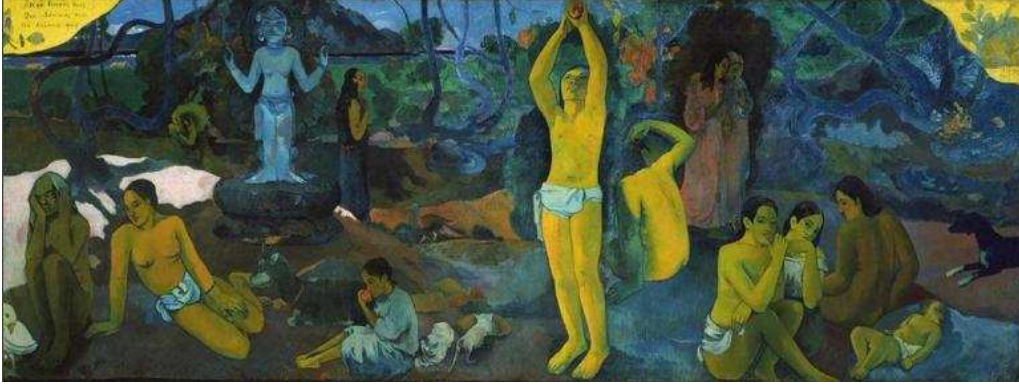
Figure 1. Gauguin's questions: D'où venons-nous? Que sommes-nous? Où allons-nous? Where are we coming from? What are we? Where are we going?
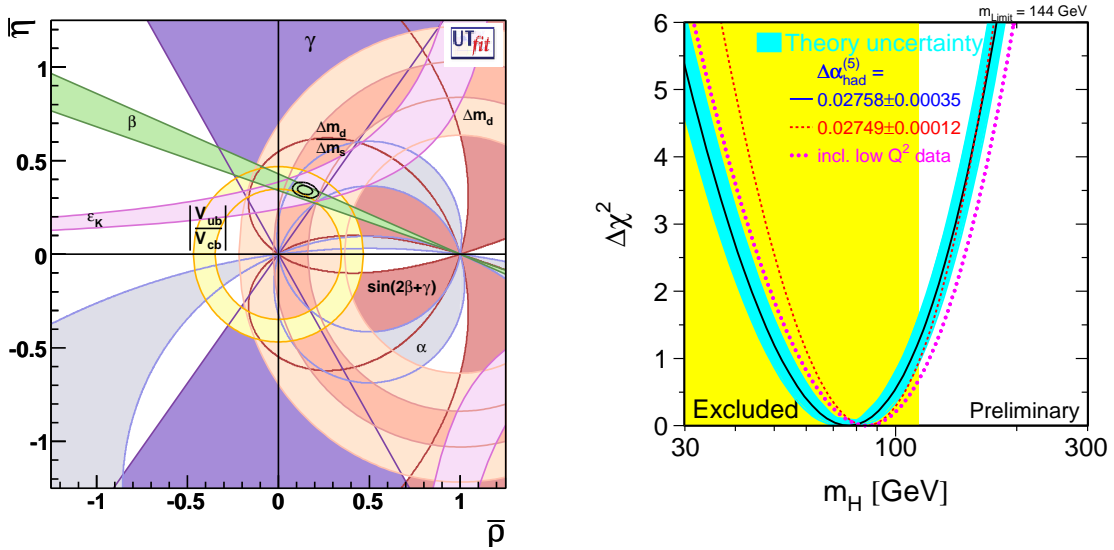
Figure 2. Two pillars of the Standard Model: the left panel shows a global fit to the Kobayashi-Maskawa quark mixing parameters [3], and the right panel shows χ^2 as a function of m_H as obtained from a global fit to precision electroweak data [7].

2.2. Precision Tests of the Electroweak Sector of the Standard Model

For over a decade now, the precision electroweak data from LEP, the SLC, the Tevatron and other experiments have not only been in very good overall agreement with the Standard Model, but have also been providing intriguing indications on the possible masses of unseen particles. The first example was the top quark, whose measured mass $m_t = 170.9 \pm 1.9$ GeV [8] agrees to better than 10 % with the value predicted within the Standard Model on the basis of precision electroweak measurements. The second example is the Higgs boson. Since the early 1990s [9], the precision electroweak data have been favouring, with increasing strength, a relatively light Higgs boson. The one-σ range currently indicated is [7]

$$m_H = 76^{+33}_{-24} \text{ GeV}, \tag{1}$$

as shown in the right panel of Fig. 2. The tendency towards a light Higgs boson has even been reinforced recently by recent measurements of m_t and m_W at the Tevatron [6]. The indication (1) is still compatible with the direct lower limit $m_H > 114$ GeV at the 15 % level, and provides a tantalizing hint on the possible nature of physics beyond the Standard Model. Broadly speaking, this would seem to favour weakly-coupled models of new physics, such as supersymmetry.

3. What Physics may lie Beyond the Standard Model?
There is a standard list of fundamental open questions beyond the Standard Model.

3.1. What is the Origin of Particle Masses?
Are they due to a Higgs boson, as hypothesized within the Standard Model? If so, is the Higgs boson accompanied by some other physics? If not, what replaces the Higgs boson? The good news is that, whatever the answers to these questions, the puzzle is likely to be solved at some energy scale below 1 TeV [10].
•Why are there so many types of matter particles?
Related to this question is the mixing of the different flavours of quarks and leptons, and the mechanism for CP violation. This matter-antimatter difference is thought to be responsible for the appearance of matter in the Universe today, and the absence of antimatter. However, the KM mechanism within the Standard Model cannot, by itself, explain the cosmological matter-antimatter asymmetry, adding urgency to the search for flavour and CP violation beyond the Standard Model [4].
• Are the fundamental forces unified?
If so, in the simplest models this unification occurs only at some very high energy $\sim 10^{16}$ GeV. Physics at this scale cannot be probed directly at accelerators, but possibly indirectly via measurements of particle masses and couplings, and looking for unification relations between them. On the other hand, models of unification may be probed more directly via neutrino physics [11].
• What is the quantum theory of gravity? (P3)
The two greatest successes of theoretical physics in the first half of the twentieth century were quantum theory and general relativity. However, we still lack a full quantum theory of gravity. The best candidate for such a theory may be (super)string theory [12], which generously predicts extra space-time dimensions as well as supersymmetry, but at what energy scale? Such a quantum theory of gravity would presumably be the long-sought 'Theory of Everything' that would answer the last of Gauguin's questions for fundamental physics.

The good news is that all of these fundamental open questions will be addressed by the LHC: its energy should be ample for resolving the problem of mass, including the questions whether there is a Higgs boson [13] and/or supersymmetry [14], a dedicated experiment will be examining matter-antimatter differences [15], models of unification could be probed via measurements of sparticle masses and couplings, and string theory might be probed via supersymmetry breaking, extra dimensions or even black hole production and decay [16]. Thus, there is a lot of exciting new fundamental physics that may be accessible to the LHC. However, some topics may only be accessible indirectly to particle accelerators, so there is also an important role for astroparticle experiments, which also bear on the cosmological aspects of Gauguin's questions.

4. What were the Early Stages of the Big Bang? (C1)
The Universe is remarkably isotropic on large distance scales, and apparently also homogeneous. We have known for some 80 years that the Universe is expanding, and for a decade or so it has been apparent that this Big Bang expansion is even accelerating [17]. The cosmic microwave background (CMB) left over from the primordial electromagnetic plasma is evidence that the visible part of the Universe was once thousands of time smaller and hotter than it is today, and
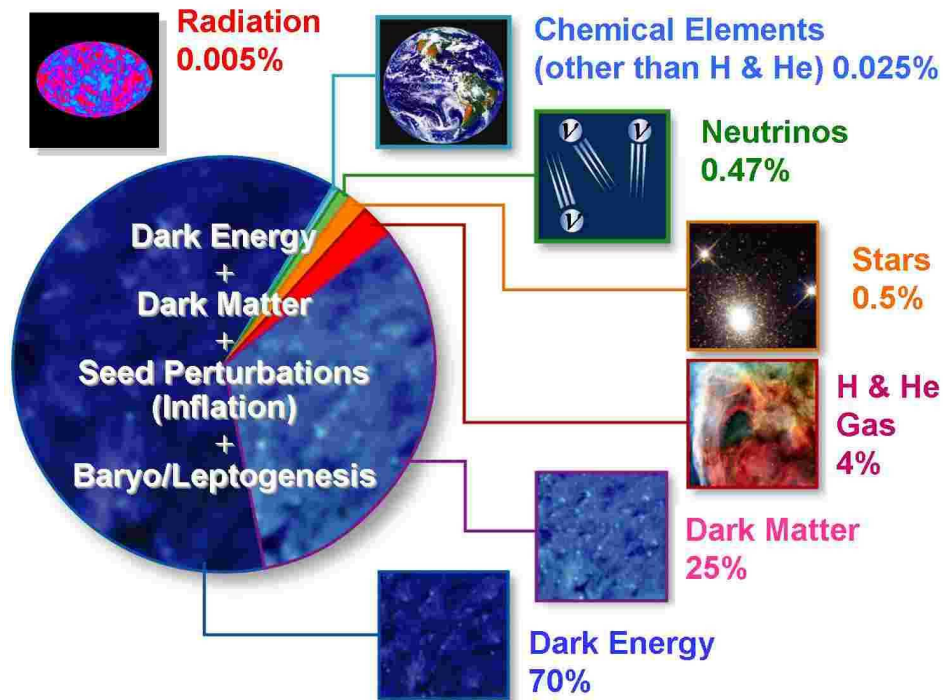
Figure 3. The toppings of the cosmic pizza [21].

the abundances of light elements indicate that the visible Universe was once a million times hotter still. So much is certainly standard. Beyond this Standard Big Bang Model of cosmology, it is believed increasingly that the Universe expanded exponentially fast at some point in its much earlier history, during an epoch of cosmological inflation [18] when quantum fluctuations appeared [19]. These are thought to have led to the small anisotropies seen in the CMB which, with the aid of cold dark matter, may have given rise to the structures seen in the Universe today.

5. What is the Material Content of the Universe Today? (C2)

The material topping of the resulting cosmic pizza has a very strange recipe [20]. As shown in Fig. 3, the visible matter makes up about 4 % of its total energy density, presumably more than neutrinos, which, in turn, contribute more than the CMB. Much more important are unidentified contributions to the energy density, namely the cold dark matter that contributes ~ 25 %, with the rest of the energy density (some 70 %) being provided by the so-called dark energy, which is not associated with matter at all, but in present even in 'empty' space.

This remarkable 'concordance model' is prompted by a number of convergent astrophysical and cosmological observations [22]. However, it begs a number of fundamental open cosmological questions:

• Why is the Universe so big and old?

The Universe is almost 14 billion years old, and many billions of light-years across, at least. Why do we live in such an atypical cosmological solution of Einstein's equations, whose only dimensional parameter corresponds to a time scale $\sim 10^{-43}$ s and a length scale $\sim 10^{-33}$ s?

• Why is the geometry of the Universe so very nearly Euclidean?

The Universe is very nearly flat, with a density that is within a % or so of the critical density for

a truly flat Universe. Cosmological inflation [18] would answer this and the previous question, but how can we test this theory?

• Where did the matter in the Universe come from?

The Universe contains about a billion photons for every proton. Why not more or less? Why any at all? The origin of matter in the Universe might be explained by a suitable CP-violating matter-antimatter asymmetry [23], but this must lie beyond the simple KM model.

• What provides the dark matter?

The betting is that takes the form of one or more varieties of weakly-interacting massive particle (WIMP), such as the lightest supersymmetric particle (LSP) [24] and/or the axion [25]. Perhaps so, but this cannot be proven by astrophysical and cosmological observations alone: the nature of the dark matter could only be established by laboratory experiments, e.g., at the LHC in the case of a WIMP such as the LSP.

• What is the nature of the dark energy? (C3)

If this is constant, as originally postulated by Einstein, then the Universe will not only expand for ever, but will end in the 'heat death' of an accelerating de Sitter phase.

This particular answer to Gauguin's last question for cosmologists may not be very inspiring, and perhaps particle physics will provide us with a more exciting answer. What is sure, though, is that we need particle physics if we are to obtain answers to any of these fundamental cosmological questions. We now see how they may be addressed by experiments at the LHC.

6. The LHC (P2, C2)

The LHC is designed primarily to collide protons with energies 7 TeV each with a luminosity of 10^{34} cm^{-2}s^{-1} [26], corresponding to a billion collisions per second, with the ability alternatively to collide heavy nuclei with energies 5 TeV per nucleon. Its primary physics targets will include the origin of mass, the nature of dark matter, the nature of the primordial quark-gluon plasma thought to have filled the Universe when it was less than a microsecond old, and matter-antimatter asymmetry. It is clear that many of these objectives are connected with Gauguin's questions in cosmology, as well as his questions in particle physics.

However, looking for the interesting new physics in proton-proton collisions at the LHC will be non-trivial. The interesting cross sections for new heavy particles will be of order $1/(\text{TeV})^2$, and many interesting new particles such as the Higgs boson have small couplings $\mathcal{O}(\alpha^2)$, whereas the total cross section is of order $1/(100 \text{ MeV})^2$. Interesting events may occur at relative rates $\sim 10^{-12}$, comparable to looking for a needle in some 100,000 haystacks.

The LHC's most anticipated discovery is surely that of the Higgs boson [27], but please do not discount it! On the one hand, the Higgs boson may not exist [28] and, on the other, even a Standard Model Higgs boson will be difficult to discover, let alone a non-standard one with stage fright. A different threat is from the Higgs searches at the Tevatron, which are advancing ominously [29]. As seen in Fig. 4, they have already reached within an order of magnitude of the cross section for a Standard Model Higgs boson with a mass just above the LEP lower limit, and are even closer to the Standard Model cross section if $m_H \sim 160$ GeV. Moreover, not all the available data have been fully evaluated, several more fb^{-1} of data are expected, and analysis techniques are constantly improving. A Standard Model Higgs boson may well be within reach of the Tevatron.

The Higgs signal at the LHC will be made up from several different signatures, such as $H \to \gamma\gamma$, $H \to WW$, $H \to ZZ^* \to 4$ leptons and $H \to \tau\tau$, which must all be combined in order to extract the Higgs signal with high significance in the early days of LHC running. This will require understanding very well details of the responses of both the ATLAS and CMS detectors. As shown in Fig. 5, estimates are that, by combining results from both detectors, it should be possible to discover a Standard Model Higgs boson at the 5-σ level with 5 fb^{-1} of data each, while 1 fb^{-1} of data each would already enable a Standard Model Higgs boson to be excluded
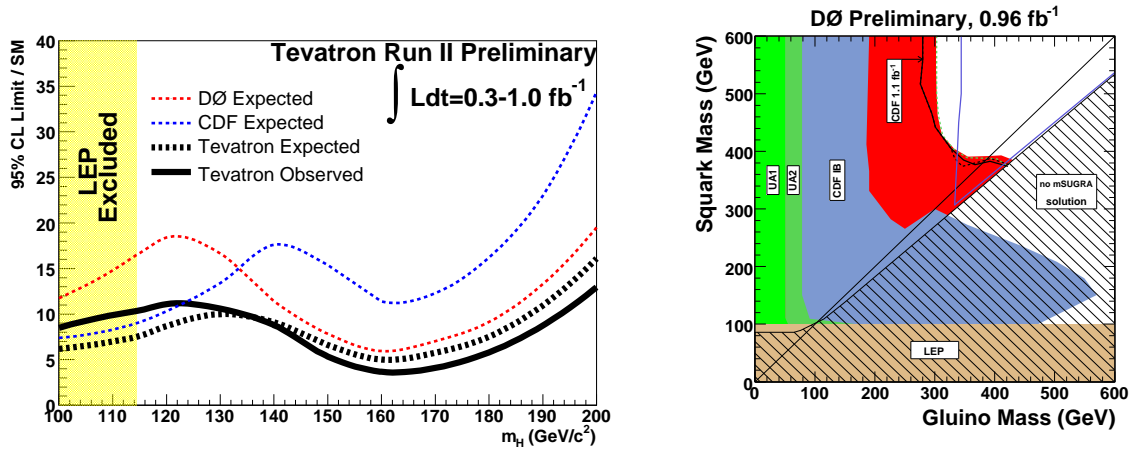
Figure 4. The Tevatron is making good running in the search for the Standard Model Higgs boson (left panel) and squarks and gluinos (right panel) [29].
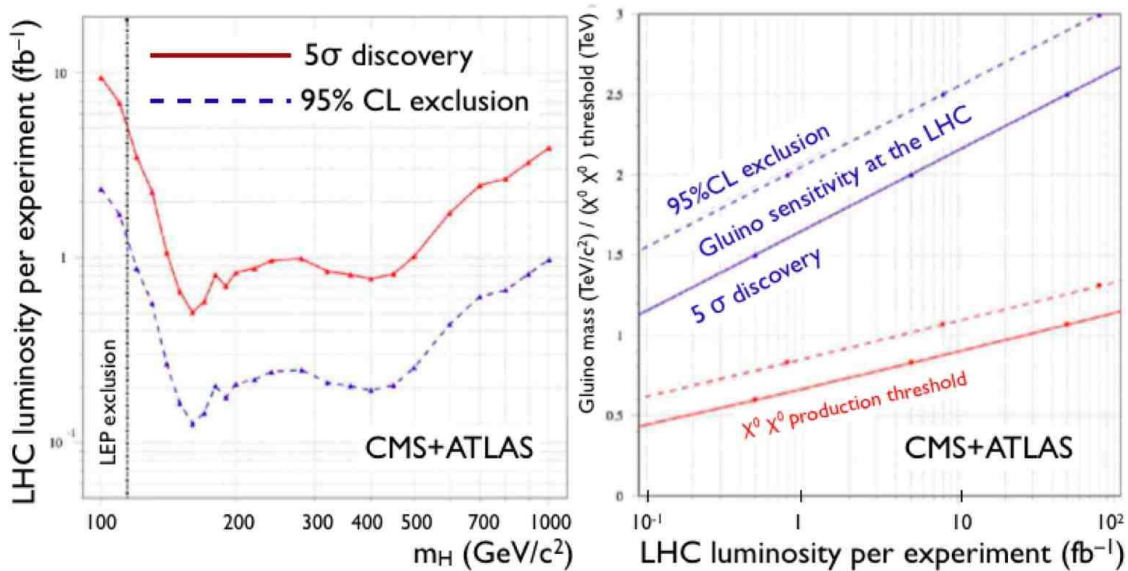

Figure 5. The combined sensitivities of ATLAS and CMS to a Standard Model Higgs boson (left), and the gluino (right), as a function of the analyzed LHC luminosity. The right panel also shows the threshold for sparticle pair production at a LC for the corresponding gluino mass, calculated within the CMSSM [30].

at the 95 % level over much of the possible mass range [30].

7. Theorists getting Cold Feet (P2)

With the discovery of the Higgs boson at either the Tevatron or the LHC becoming increasingly imminent, it seems that many theorists are getting cold feet, or at least hedging their bets by dusting off alternative theories [31], many of which are related, as shown in Fig. 6.

• Perhaps the elementary Higgs boson of the Standard Model should be replaced by some composite alternative?
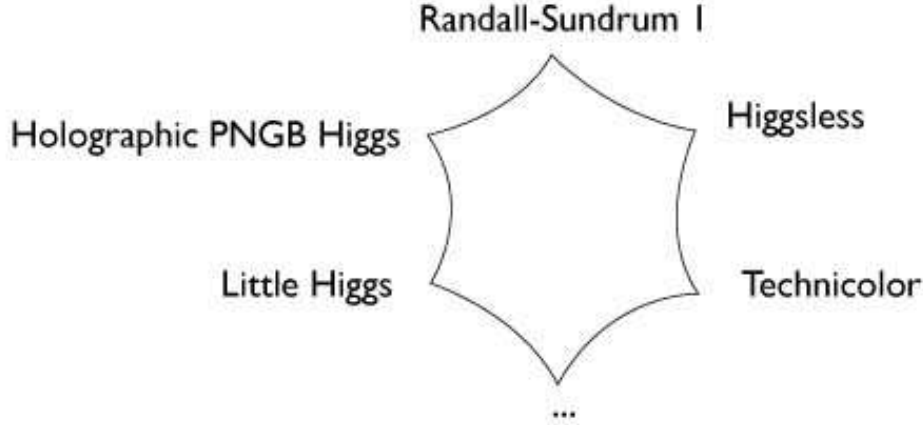
Figure 6. An illustration of the space of possible alternatives to supersymmetry at low energies [31].

(Un)fortunately, at least simple technicolour models of this type run into conflict with the precision electroweak data discussed earlier.

• So, perhaps the interpretation of the electroweak data is at fault [32]?
There are issues with the mutual consistency of the measurements, so perhaps some should be discarded, or perhaps some new physics should be invoked to reconcile them? In either case, the usual prediction of the mass of the Standard Model Higgs boson would be invalidated.

• Alternatively, perhaps the Standard Model Higgs boson is the right hypothesis, but perhaps it is supplemented by higher-dimensional operators that allow the mass range expected for the Higgs boson to be extended beyond (1), by opening up a corridor to heavier higher Higgs masses [33]?

• Another interesting new class of Higgs scenarios comprises the so-called Little Higgs models [34], see Fig. 6, which offer novelties such as an extra 'top-like quark, gauge bosons, and exotic Higgs bosons.

• Finally, there are the 'nightmare' scenarios offered by Higgsless models [28], also seen in Fig. 6. In their original four-dimensional versions, these predicted strong WW scattering at the TeV scale which led, via loop effects, to incompatibilities with the precision electroweak data. In order to mitigate this risk, it was proposed to break the electroweak symmetry by boundary conditions in an extra dimension, which enabled strong WW scattering to be delayed until ~ 10 TeV. Even so, issues of compatibility with precision electroweak data persist. Moreover, and rather encouragingly, even if one could construct such a Higgsless scenario, the likelihood is that it would have other observable signatures such as Kaluza-Klein modes associated with the extra dimension.

There is some debate what would be the maximum conceivable disaster scenario for the LHC, assuming that the accelerator and the detectors work as designed. Some might say that a Higgsless scenario would be disastrous, and it might indeed be difficult to explain to funding agencies and politicians. On the other hand, it could be a very promising avenue into extra space dimensions, which would arguably be more exciting then 'only' finding a Standard Model Higgs boson. A much duller scenario might be to discover a Standard Model Higgs boson with a mass ~ 180 GeV, in which case the renormalization group would permit you to run the Standard Model parameters all the way to the Planck mass, and there might be no new physics before quantum gravity sets in [35].
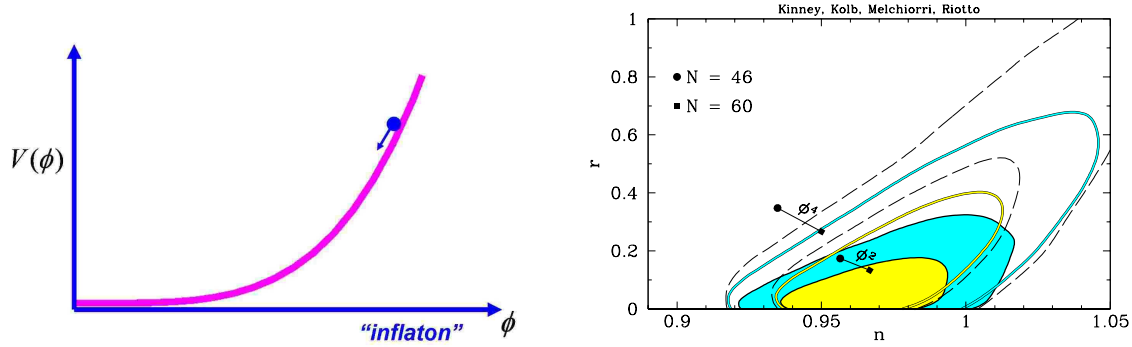
Figure 7. Left panel: Inflation is driven classically by the vacuum energy associated with the potential $V(\phi)$ of a scalar inflaton field ϕ [18]. Right panel: Quantum fluctuations in ϕ would produce density perturbations [19], and present measurements by WMAP *et al.* favour marginally a potential $V \sim \phi^2$ [37].

8. The Stakes in the Higgs Search (P2)

There should be no misunderstanding: the stakes in the Higgs search are very high. Within fundamental physics, issues are the manner in which gauge symmetry is broken, and whether there is any elementary scalar field. However, the stakes for cosmology are also very high. An elementary Higgs boson would have caused a phase transition in the early Universe, when it was $\sim 10^{-12}$ s old (C1). It might, at that epoch, have generated the matter in the Universe via electroweak barygenesis (C2). Further back in the history of the Universe, a related inflaton [18] might have expanded the Universe exponentially when it was $\sim 10^{-35}$ s old (C1, C2), as illustrated in Fig. 7. Coming back to the present, naively the Higgs boson of the Standard Model would contribute a factor $\sim 10^{56}$ too much to the present-day dark energy (C3), apparently requiring some 'miraculously' fine-tuned cancellation. Cosmologists should be as interested as particle physicists in the dénouement of the Higgs saga.

9. The LHC of Cosmology? (C1, C2)

In parallel with the operation of the LHC, cosmologists will have the Planck satellite, a new tool for analyzing the CMB that has similar potential for exploration within and beyond the Standard Model of cosmology [36]. Its probes of the spectrum of primordial density perturbations up to very high multipoles will provide stringent consistency tests of the inflationary idea illustrated in Fig. 7. Planck measurements should also be able to distinguish between specific models and yield detailed information about the effective inflationary potential: is $V \sim \phi^n, e^{-\lambda\phi}$ or ...? Planck measurements will enable the inflationary potential to be reconstructed over some range of values of the inflaton field ϕ. Measurements of the spectral index n_s of the scalar component of the perturbations, and the ratio r of tensor perturbations to scalar perturbations may discriminate between, e.g., a quadratic potential $V \sim \phi^2$ and a quartic potential $V \sim \phi^4$. There is already some preference for the simplest ϕ^2 [37], as seen in Fig. 7.

Even if one accepts the inflationary paradigm, there are many options to distinguish. Is the inflaton an elementary scalar field, or is it some composite effective field that reflects more complex quantum-gravitational (string?) dynamics? If there is an elementary inflaton field, what is it? There is no candidate for the inflaton within the Standard Model of particle physics: could it arise from some simple extension of the Standard Model, or might it be some dilaton of string theory?

It is a challenge to relate the hypothetical inflaton to some recognizable particle physics. One of the simplest possibilities is that the inflaton is a spartner of one of the singlet (right-handed) neutrinos in a seesaw model of neutrino masses [38]. This would have an effective $m^2\phi^2$ potential, and the magnitude of the density perturbations observed by COBE, WMAP et al. fix $m \sim 2 \times 10^{13}$ GeV, which fits well within the expected range of singlet neutrino masses. The decay of the singlet neutrino could then generate the baryon asymmetry without further ado [39].

10. The Higgs Boson and Vacuum Energy (C3)

As naively written: $V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$, the effective Higgs potential would have a negative value at its minimum, which would be about 56 orders of magnitude larger than the physical value of the dark energy density. If particle theorists think about it at all, they just add a constant to the effective Higgs potential, so as to cancel this unwanted value to the desired 56 decimal places. This is just one aspect of the fine-tuning problem posed by the dark energy. There is also a contribution to the vacuum energy from the QCD vacuum that is some 44 orders of magnitude too large. fashionable models of grand unification provide some 110 orders of magnitude too much vacuum energy, and a generic model of quantum gravity is likely to provide some 120 orders of magnitude too much! It seems clear that understanding the observed magnitude of the dark energy is going to require some new physics. At the moment, all the data are consistent with constant vacuum energy at the present epoch, in which case the Universe will expand exponentially for the foreseeable future.

11. Supersymmetry (P2)

My personal favourite candidate for (part of) this new physics is supersymmetry which, with some luck, could even be the LHC's first discovery. There are several reasons for liking supersymmetry: it is intrinsically beautiful, it may help unify the different fundamental interactions, it is (almost) an essential ingredient in string theory, etc. However, there are four specific reasons why one might expect supersymmetry to appear around the TeV scale, and hence be accessible to the LHC. One is the naturalness or hierarchy problem [40], another is the unification of the gauge couplings [41], another is the supersymmetric prediction of a light Higgs boson [42] as preferred by the precision electroweak data, and another is that many supersymmetric models predict the existence of cold dark matter with a density comparable to that required by astrophysics and cosmology [24].

Supersymmetry helps make the hierarchy of mass scales in physics more natural [40], by cancelling the quadratic divergences that arise from individual loop diagrams with fermions and bosons:

$$
\begin{aligned}
\Delta m_H^2 &= -\frac{y_f^2}{16\pi^2}[2\Lambda^2 + 6m_f^2\ln(\Lambda/m_f) + ...], \\
\Delta m_H^2 &= -\frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2\ln(\Lambda/m_S) + ...].
\end{aligned}
\tag{2}
$$

We see immediately that the leading quadratic divergences cancel if $\lambda_S = 2y_f^2$, which is exactly the relation imposed by supersymmetry. Even more remarkably, this cancellation persists to all orders in perturbation theory, rendering a light Higgs boson technically natural if the supersymmetric partners of the Standard Model particles weigh less than ~ 1 TeV. Remarkably, if sparticles have masses in this range, within range of the LHC, detailed calculations show that they would improve the renormalization-group unification of the gauge couplings [41], and that the lightest supersymmetric particle (LSP) could provide the cold dark matter advocated by astrophysicists and cosmologists (C2) [24].
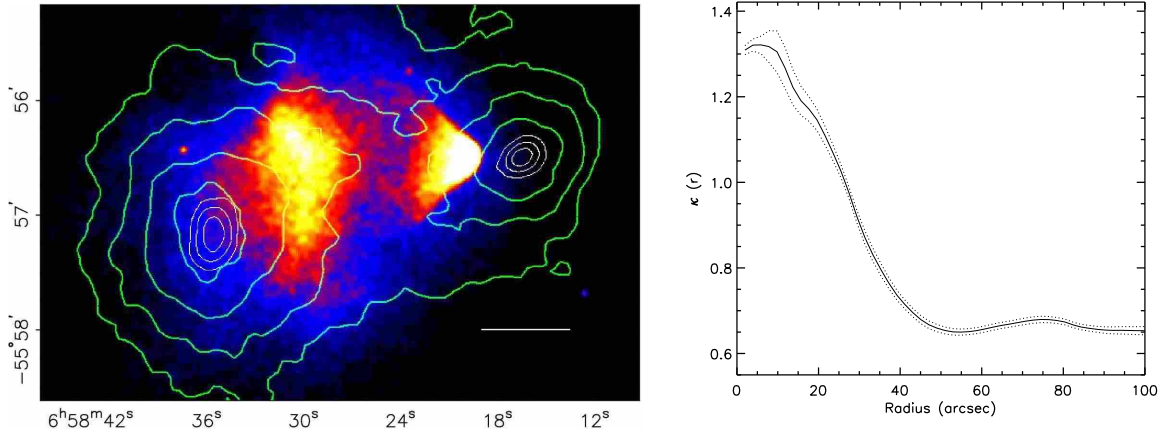
Figure 8. Collisions between clusters of galaxies provide direct proof for weakly-interacting dark matter. In the left panel, two clusters have collided transverse to our line of sight, and their dark matter cores have passed through each other essentially unscathed (contours), whereas the associated gas seen between them has collided and heated up [43]. In the right panel, two clusters have collided along our line of sight, and the radial distribution of the dark matter has been perturbed, with a depletion at a radius ~ 50 arcsec and an enhancement at a radius ~ 75 arcsec [44].

12. Direct Evidence for Cold Dark Matter (C2)

In the past year, several dramatic pieces of direct evidence for collisionless dark matter have emerged. For example, the results of a collision between two clusters of galaxies moving across our line of sight have been observed, as shown in the left panel of Fig. 8 [43]. Weak lensing of background objects shows that the dark matter haloes in which the clusters are embedded have passed through each other essentially without perturbation, whereas the gas clouds in the cluster have collided and heated up, presumably because the gas molecules have much stronger interactions than the dark matter particles. Another example is of the collision of two clusters along our line of sight, shown in the right panel of Fig. 8 [44]. In this case, a small perturbation is seen in the radial distribution of the cold dark matter, consistent with the expected tidal disruption expected from gravitational interactions between the dark matter particles (cf, the 'beam disruption parameter' familiar at linear colliders). Thirdly, obervations of weak lensing at different wavelengths (and hence coming on average from different redshifts) has made possible a three-dimensional deconstruction of the cold dark matter distribution, revealing a large scaffolding to which visible matter is attached, shown in Fig. 9 [45].

13. Constraints on Supersymmetry (P2)

There are direct limits on sparticle masses from their absences at LEP and the Tevatron, and indirect constraints from the LEP lower limit $m_h > 114$ GeV and from B physics, including in particular measurements of $b \to s\gamma$ decay. One possible indication of new physics at the TeV scale may be provided by the BNL measurement of the anomalous magnetic moment of the muon [46], that seems to exhibit a three-σ discrepancy with the Standard Model, though this is still somewhat controversial [6]. The strongest constraint on (one combination of) supersymmetric model parameters is provided by the density of cold dark matter: $0.094 < \Omega_\chi h^2 < 0.124$ [21], assuming that it is mainly composed of the lightest neutralino χ. This not the only possibility: presumably the LSP should have neither strong nor electromagnetic interactions [24], but there
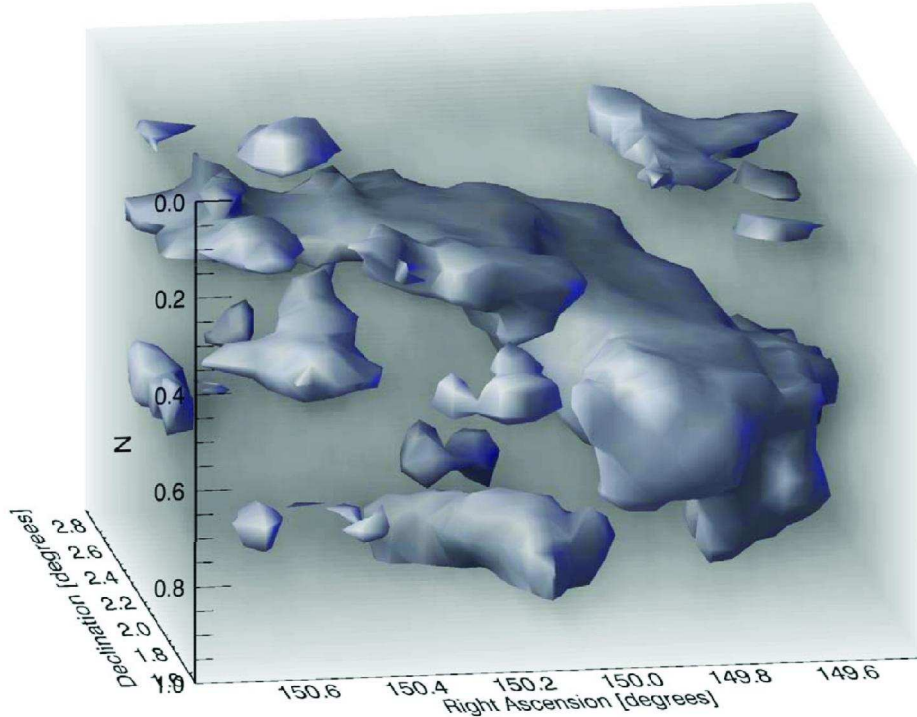
Figure 9. A three-dimensional reconstruction of the scaffolding of dark matter, as determined using weak lensing of light at different wavelengths, originating on average from different redshifts [45].

are other candidates that also have these properties. The supersymmetric partners of the neutrinos have been excluded by a combination of LEP and direct dark matter searches, but the LSP might be the spartner of some particle beyond the Standard Model, such as the gravitino.

In a minimal supersymmetric model with universal soft supersymmetry-breaking parameters, one may consider constraints in the $(m_{1/2}, m_0)$ plane, where $m_{1/2}$ is the universal soft supersymmetry-breaking gaugino mass, and m_0 is the universal soft supersymmetry-breaking scalar mass. Regions of this plane are excluded, in particular, by the requirement of a neutral LSP, by m_h, by $b \to s\gamma$, by the dark matter density and (maybe) by $g_\mu - 2$. As shown in the left panel of Fig. 10 [47], the resulting allowed regions are narrow strips near boundaries where $m_0 \sim 200$ GeV and $m_\chi \sim m_{\tilde{\tau}_1}$, and where $m_0 > 1$ TeV and electroweak symmetry breaking is no longer possible (which is disfavoured by $g_\mu - 2$).

Along these strips, $m_{1/2}$ may become quite large, and hence even the lightest visible supersymmetric particle may become quite heavy, as shown in the right panel of Fig. 10 [48]. Within a large sample (red points) of CMSSM parameter choices, models yielding a suitable dark matter density are shown in blue. Supersymmetric particles would be detectable at the LHC in most (but not all) of these models (green points), whereas the direct detection of supersymmetric dark matter might be possible only if the sparticles are relatively light (yellow points).

As shown in Fig. 11 [49], a global fit to precision electroweak and B-decay observables indicates a preference for relatively small values of $m_{1/2}$. This is due predominantly to $g_\mu - 2$ [46], but there is some support from the measurements of m_W. Correspondingly, the most likely value for the mass of the lightest supersymmetric Higgs boson is only slightly above the LEP lower limit.
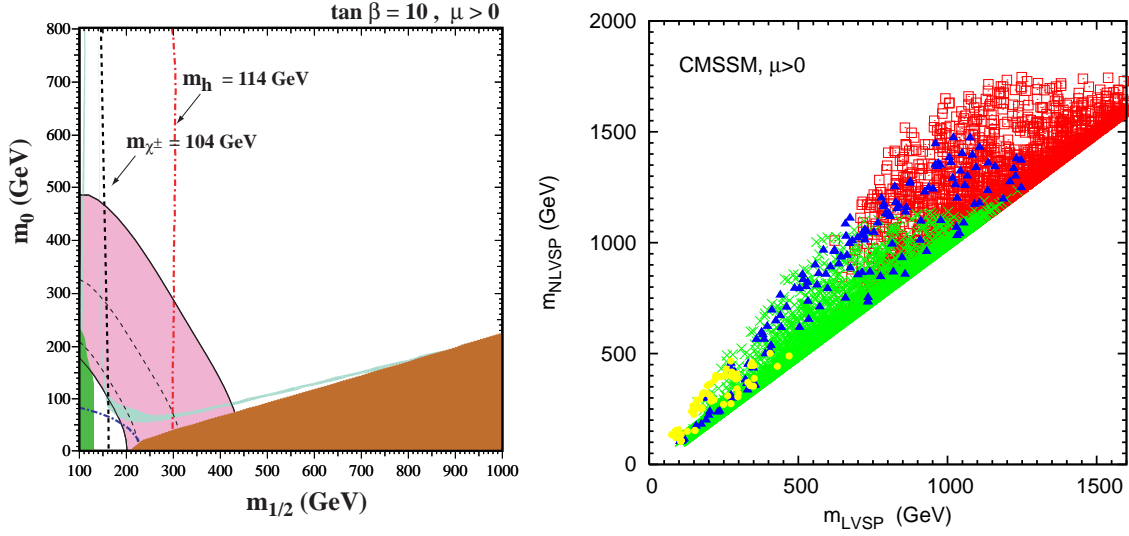
Figure 10. Left panel: The $(m_{1/2}, m_0)$ plane in the CMSSM for $\tan\beta = 10$, $\mu > 0$ and $A_0 = 0$ [47], incorporating the theoretical, experimental and cosmological constraints described in the text. Right panel: The masses of the lightest and next-to-lightest visible supersymmetric particles in a sampling of CMSSM scenarios [48]. Also indicated are the scenarios providing a suitable amount of cold dark matter (blue), those detectable at the LHC (green) and those where the astrophysical dark matter might be detected directly (yellow) [48].
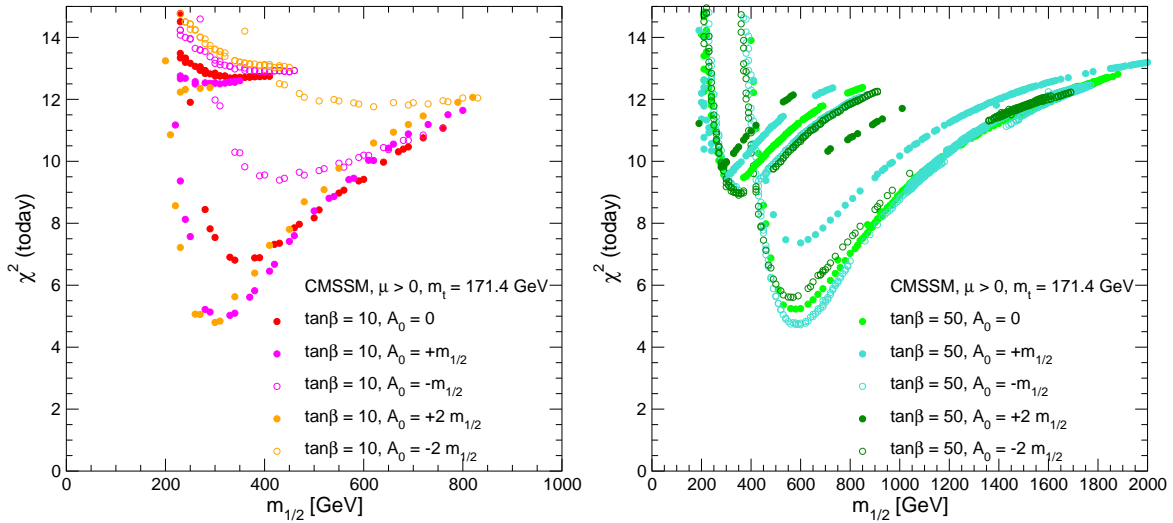
Figure 11. The combined χ^2 function for electroweak precision observables and B-physics observables, evaluated in the CMSSM for $\tan\beta = 10$ (left) and $\tan\beta = 50$ (right) for various discrete values of A_0. We use $m_t = 171.4 \pm 2.1$ GeV and $m_b(m_b) = 4.25 \pm 0.11$ GeV, and m_0 is chosen to yield the central value of the cold dark matter density indicated by WMAP and other observations for the central values of m_t and $m_b(m_b)$ [49].

14. Searching for Supersymmetry (P2)

The classic signature of sparticle production is the appearance of events with missing energy-momentum carried away by invisible dark matter particles. Studies indicate that such a signature should be observable at the LHC above instrumental and Standard Model backgrounds. As shown in the right panel of Fig. 5 [30], it is estimated that 0.1 fb^{-1} of LHC luminosity would be sufficient to observe a gluino with a mass of 1.2 GeV at the five-σ level, or to exclude a gluino weighing < 1.5 TeV. The discovery and exclusion reaches would extend to about 2.2 and 2.5 TeV, respectively with 10 fb^{-1} of LHC luminosity.

As also shown in the right panel of Fig. 5, assuming universal input sparticle masses at the GUT scale, are the corresponding thresholds for sparticle pair production at a linear e^+e^- collider would be 0.5 (0.6) or 0.8 (1.0) TeV [30]. Hence, for example, if the LHC discovers the gluino with 0.1 fb^{-1}, one may expect that sparticle pair production would be accessible to a linear collider with centre-of-mass energy of 0.5 TeV, whereas if the LHC does not discover the gluino even with 10 fb^{-1}, the e^+e^- sparticle pair production threshold may be above 1 TeV. At least in such a simple model, the LHC will tell us how much energy a linear collider would need to find supersymmetry. If Nature is kind, and sparticles not only exist but also are quite light, it will be possible to test directly unification of the gauge couplings and universality of the soft supersymmetry-breaking scalar masses with high precision, in particular by comparing measurements at the LHC and the ILC or CLIC.

15. The Stakes in the SUSY Search (P2)

The stakes in the search for supersymmetry are very high. Supersymmetry would be a completely novel symmetry, never seen before in Nature at the fundamental level. It would correspond, in a sense to a novel 'quantum' extension of the notion of space to 'superspace'. It would provide a circumstantial hint for string theory, which depends (almost) on its existence. In addition to these fundamental insights, supersymmetry would also stabilize the hierarchy of mass scales in physics, might explain 90 % of the matter in the Universe, and would facilitate the unification of the fundamental forces. No wonder that so many theorists are so enamoured of SUSY, and even some experimentalists! As seen in the right panel of Fig. 5, we might be lucky at the LHC and see supersymmetry quite quickly, if the sparticles are light. Equally, however, we may need to be patient. There is not a complete guarantee that SUSY will be found at the LHC, even if it does provide the dark matter, and a linear e^+e^- collider may need a centre-of-mass energy in the multi-TeV range to be reasonably sure of observing even the lightest visible supersymmetric particle [48].

16. Search for a 'Theory of Everything' (P3)

The two greatest achievements of twentieth-century physics, namely quantum mechanics and gravity, are still not combined. Moreover, we do not have a unified description of gravity and the other fundamental interactions, whose carrier particles have different spins. The 'only game in town' for solving these problems seems to be string theory [12]. As already mentioned, strings seem (almost) to require supersymmetry, and also revive the suggestion that there may be additional dimensions of space.

In addition to its candidature as a 'Theory of Everything', string theory provides us with a tremendously powerful new theoretical toolbox that goes beyond traditional quantum field theory in many ways. The insights it provides have many other potential appliactions to more mundane problems, such as perturbative calculations in QCD [50] and the nature of the quark-gluon plasma [51].

The full enormity of the ambiguity in the string vacuum has sunk in only recently, with numbers $\mathcal{O}(10^{500})$ being bandied about [52]. This ambiguity arises because there are certainly millions and perhaps billions of consistent compactifications of strings on manifolds in extra

dimensions, and each of these has dozens or hundreds of topological cycles through which there may be topological fluxes taking any of dozens of values. Somewhere in this landscape of an enormous number of string vacua, it is suggested there may be one with a vacuum energy in the range indicated by the cosmology dark energy. The question then arises how the Universe chooses which of these vacua. One may also wonder whether, since nature apparently has the opportunity to choose a small vacuum energy, perhaps it also chooses a small value of m_W, and there is no need for supersymmetry to render the choice natural [53].

I was recently asked to give to young string theorists some introductory lectures on LHC physics, and I peppered my lectures with the following ten questions for string theorists:

• Can you derive (something like) the Standard Model from string, with the appropriate SU(3)×SU(2)×U(1) gauge group, without too many unseen additional particles, and does your derivation provide useful constraints on the many arbitrary parameters of the Standard Model?

• Can you calculate the vacuum energy? Preferably, do not cop out by invoking the landscape!

• Are you able to live with a cosmological constant? Traditional string theory is based on the existence of an S matrix, but this does not exist in a de Sitter space, as would be required if the vacuum energy is truly constant [54]. In such a case, scattering is described by a superscattering $ matrix [55].

• Do you have any new ideas for avoiding the existence of a Higgs boson? This would require developing innovative strategies for gauge symmetry breaking, e.g., via boundary conditions in extra dimensions.

• Will your string-inspired techniques in perturbative QCD enable better calculations of Higgs production and decay?

• Can you improve perturbative QCD techniques sufficiently to improve calculations of the backgrounds to Higgs production and decay?

• Is supersymmetry really essential for string theory and, if so, are you able to offer any hint on the scale of superymmetry breaking?

• What is the pattern of supersymmetry breaking and, in particular, what are the relative values of m_0 and $m_{1/2}$, and are they universal?

• If they are universal, what is the scale where supersymmety-breaking parameters appear to be unified, and does supersymmetry breaking appear below the GUT/string scale?

• How large might extra dimensions be and, in particular, is there any reason to expect them below the GUT/string scale?

Answers to any of these questions would be a tremendous success for string theorists, and help to quieten down the doubters.

17. How Large could Extra Dimensions be? (P2)

As already mentioned, one of the possibilities offered by string theory is that there might be extra dimensions: how large could they be? When string theory was originally proposed as a 'Theory of Everything', it was imagined that all the extra dimensions would be curled up on length scales comparable to the Planck length $\sim 10^{-33}$ cm. However, then it was realized that string unification could be achieved more easily if one of these dimensions was somewhat smaller than the GUT scale [56], and a number of scenarios with much larger extra dimensions have been considered. For example, an extra dimension of size ~ 1 TeV^{-1} could help break supersymmetry [57] and/or the electroweak gauge symmetry, an extra dimension of micron size could help rewrite the hierarchy problem [58], and even infinite extra dimensions are allowed if they are warped appropriately [59].

In many of these scenarios, there are potential signals to be found at the LHC, such as Kaluza-Klein excitations of gravitons, or missing energy 'leaking' into an extra dimension. The most spectacular possibility would occur if gravity becomes strong at the TeV energy scale,

in which case microscopic black holes might be produced at the LHC. These would be very unstable, decaying rapidly via Hawking radiation into multiple jets, leptons and photons [16].

18. Conclusions

These examples have shown that high-energy accelerators such as the LHC are telescopes as well as microscopes. They are able to address Gauguin's questions for cosmology and astrophysics, as well as in particle physics itself. We do not know what the LHC will find, but surely Gauguin would be happy with some of the answers it will provide.

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