

LOOKING BACK AT THE FIRST DECADE OF 21ST-CENTURY HIGH-ENERGY PHYSICS

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On the occasion of the Tenth Conference on String Phenomenology in 2011, I review the dramatic progress since 2002 in experimental tests of fundamental theoretical ideas. These include the discovery of (probably fermionic) extra dimensions at the LHC, the discovery of dark matter particles, observations of charged-lepton flavour violation, the debut of quantum gravity phenomenology and the emergence of space-time from the string soup.

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1. Introduction

The organizers of the Tenth Conference on String Phenomenology, $\cos^{10} \phi$, have invited me to review the exciting developments in high-energy physics that took place during the tumultuous first decade of the 21st century. It is amusing to look back at the quaint preoccupations of participants in the first $\cos \phi$ meeting, back in 2002. At that time, accelerators had established what was then regarded as the Standard Model, but offered no clear indications what directions physics might take beyond it, and the community was anxious for the LHC to be funded and completed. On the other hand, non-accelerator experiments had provided evidence beyond the Standard Model in the form of neutrino oscillations. Meanwhile, string theorists were all doing PP or branes in extra dimensions.

How different is today's panorama! The LHC has taken us triumphantly beyond the Standard Model, and its financial travails back in 2002 have been long forgotten. However, now we are anxious for the linear e^+e^- collider to be funded and completed. In parallel, cosmology has taken us far beyond the petty models for physics beyond the Standard Model that

we were playing with back in 2002. Quantum gravity has now become an experimental science, and we are probing directly the emergence of space-time itself.

There is no point in reviewing here the discovery of the Higgs boson ¹. That is an old story by now, prefaced by the evanescent hint at LEP ², the suspense maintained by the data from the Tevatron ³, and climaxed by the prompt appearance of the Higgs boson at the LHC, as illustrated in Fig. 1. The most important remaining Higgs question is whether the LHC will be able to discover its partners that are expected in the Minimal Supersymmetric Standard Model (MSSM). As seen in Fig. 2, it is touch-and-go whether the LHC will be to find these heavier MSSM Higgs bosons, though the LHC luminosity upgrade to $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ currently underway will certainly improve the chances ⁴.

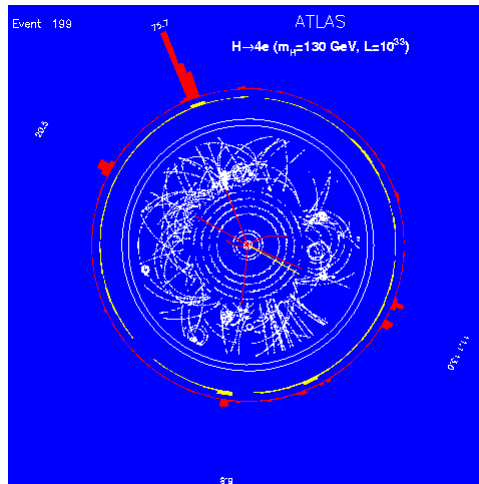


Figure 1. One of the first Higgs events observed at the LHC by the ATLAS collaboration, in which the Higgs boson decays into $e^+e^-e^+e^-$.

Rather than the old Higgs story, here I focus on the most important discovery of the LHC to date, namely

2. Discovery of Extra Dimensions

The issue was never really whether the LHC would discover extra dimensions, but whether they would be bosonic: $x_{5,6,\dots}$ or fermionic: $\theta, \bar{\theta}$. Long before the LHC, it was pointed out that one of the most promising sets of signals for supersymmetry would be events with missing transverse en-

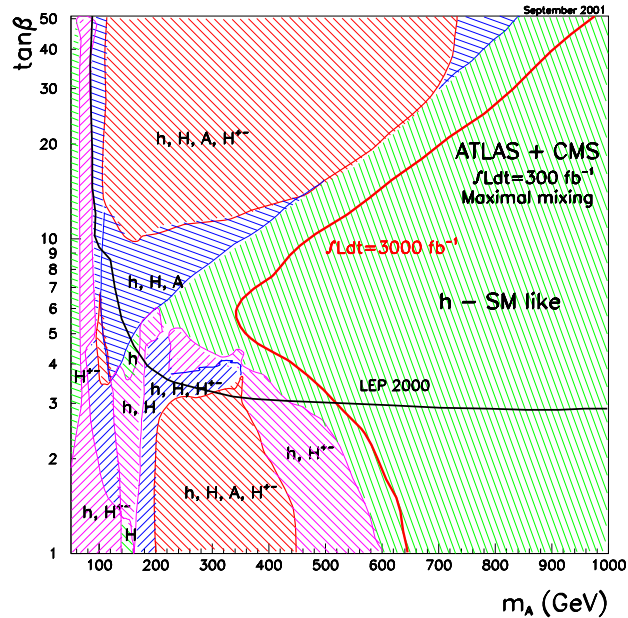


Figure 2. Illustration of the improved reach for heavier MSSM Higgs bosons expected with the LHC upgrade to $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ now underway.

ergy, accompanied by hadronic jets and/or leptons produced in the cascade decays of heavier sparticles, as seen in Fig. 3⁵. Events resembling these predictions were indeed found almost as soon as the LHC switched on, see for example Fig. 4¹. However, already back in 2002, it had been pointed out that universal extra-dimensional models with conserved Kaluza-Klein parity also predict missing-energy events. Just like the sparticle cascades, the sequential decays of Kaluza-Klein states produce accompanying jets and leptons, as seen in Fig. 5⁶.

Of course, distinguishing the supersymmetric and Kaluza-Klein scenarios turned out to be relatively simple, in principle. For similar masses, the cross sections at the LHC were different, as well as their angular distributions. Moreover, the mass differences between different Kaluza-Klein states were relatively small, as seen in Fig. 6⁶, because of the small renormalization-group range compared with the GUT scale anticipated in supersymmetry. Using these clues, the supersymmetric interpretation of the LHC missing-energy events has gained the upper hand, though there may still be some die-hard advocates of the Kaluza-Klein interpretation.

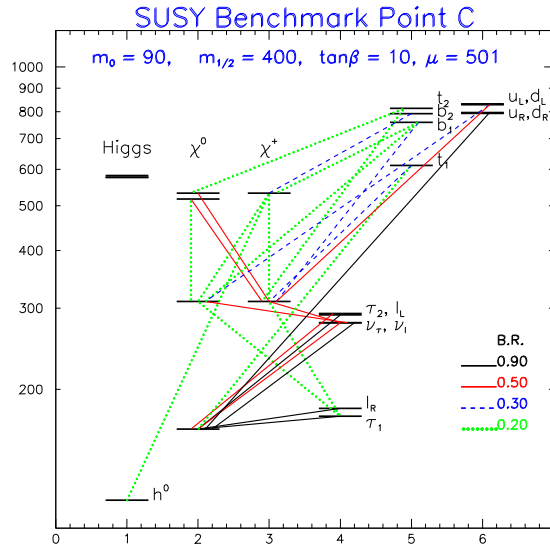


Figure 3. Typical example of the cascades of sparticle decays expected in a scenario with fermionic extra dimensions at the LHC, which is to be distinguished from the type of cascade expected in a scenario with bosonic extra dimensions, as illustrated in Fig. 5.

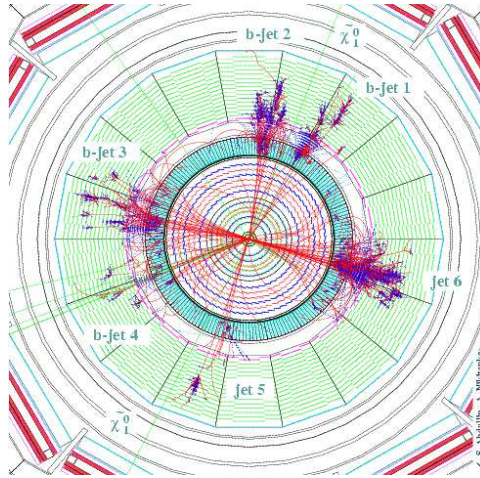


Figure 4. One of the first supersymmetric candidate events observed at the LHC by the CMS collaboration. This event includes two energetic jets, three leptons and missing energy.

The discovery of supersymmetry at the LHC certainly did not come as a surprise, since most of the allowed parameter space was known to be accessible to the LHC, as foreshadowed in Fig. 7⁵. However, the initial LHC configuration has not been able to measure all the sparticle masses and other properties one should like to know, providing a second motivation

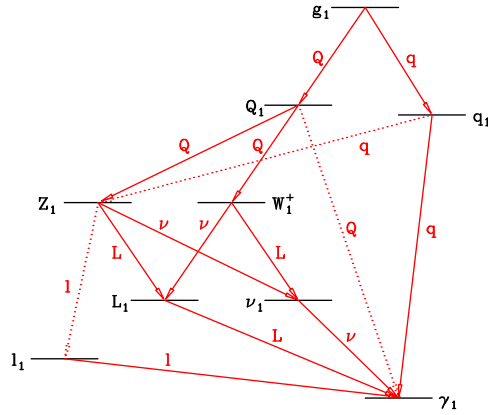


Figure 5. Typical example of the cascades of Kaluza-Klein excitation decays expected in a scenario with universal bosonic extra dimensions at the LHC, which is to be distinguished from the type of cascade expected in a scenario with fermionic extra dimensions, as illustrated in Fig. 3.

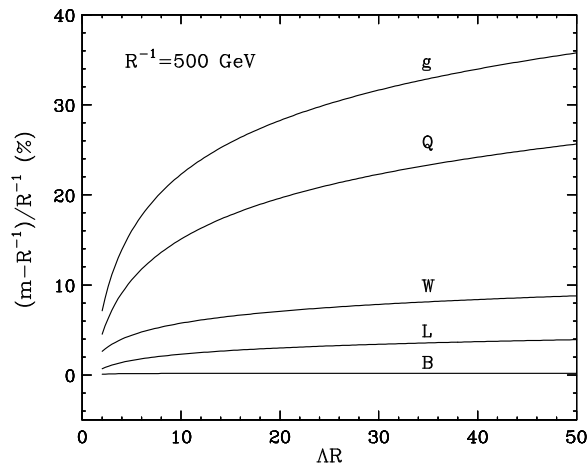


Figure 6. Sample calculation of the renormalization of the masses of Kaluza-Klein excitations in a model with universal extra dimensions.

for the LHC luminosity upgrade, as seen in Fig. 8⁴.

The community has long known that the TeV-scale linear collider now under construction would be needed to unravel sparticle (or Kaluza-Klein) spectroscopy, which is why we have been so anxious about its financing. Just as the corresponding LHC problems were overcome in 2002, we have been relieved this year that the analogous linear collider issues have also

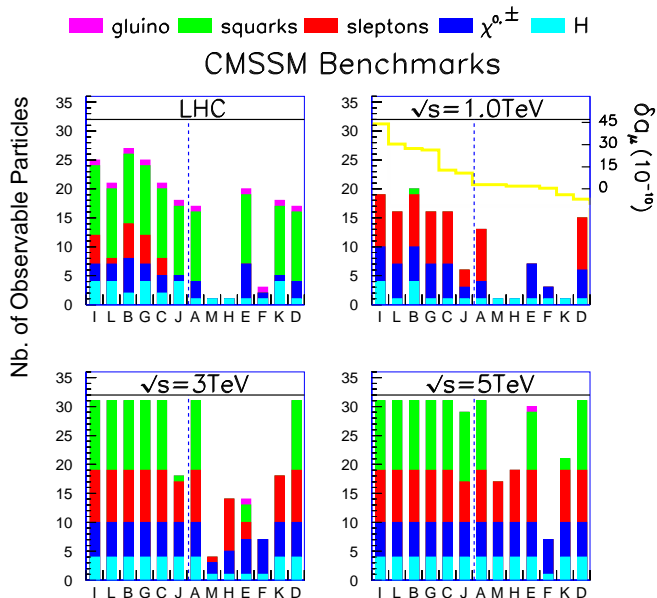


Figure 7. Examples of the numbers of different states in scenarios with extra fermionic dimensions that are observable at different colliders.

been resolved. We look forward soon to detailed measurements of Higgs decay branching ratios, which may tell us indirectly whether the heavier supersymmetric Higgs bosons are really there, and to better measurements of the sparticle (or Kaluza-Klein) masses. These will finally lay to rest the debate between gravity-mediated and other scenarios for supersymmetry breaking, and perhaps even finally convince Kaluza-Klein die-hards that the extra dimensions are indeed fermionic.

Their last-ditch stand has, however, been encouraged by the remarkable LHC event reported last year, shown in Fig. 9, which has all the characteristics expected of TeV-scale black-hole production ⁷. It has many jets, predominating over leptons and missing energy. Time and the LHC luminosity upgrade will tell us whether this was a statistical fluctuation or a harbinger of Hawking radiation.

3. Discovery of Dark Matter

It was known at the beginning of the past decade that astroparticle experiments would have a fair chance of detecting supersymmetric dark matter,

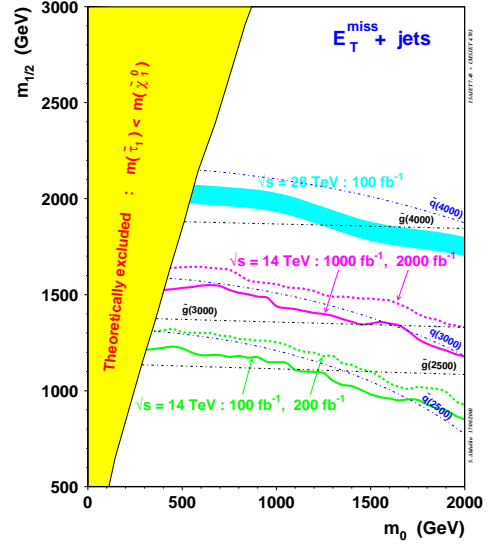


Figure 8. The LHC luminosity upgrade to $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ will enable the physics reach for particles and extra bosonic dimensions to be extended significantly.

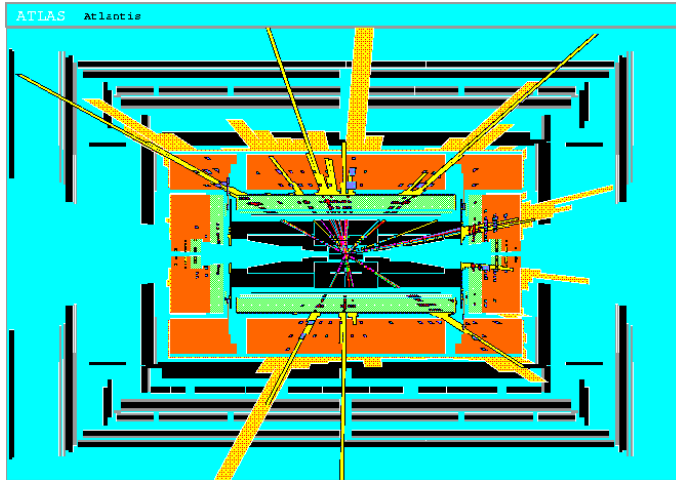


Figure 9. Candidate for a black-hole production event recently observed at the LHC.

if it existed. The direct search for the scattering of dark-matter particles in the laboratory has not yet been successful, despite the best efforts of the CDMS collaboration in the Soudan mine ⁸. However, the recent ob-

servations by IceCube⁹ of energetic muons from the direction of the Sun, believed to originate from the interactions of energetic solar neutrinos, are compatible with several of the benchmark supersymmetric scenarios proposed a decade ago, as seen in Fig. 10¹⁰.

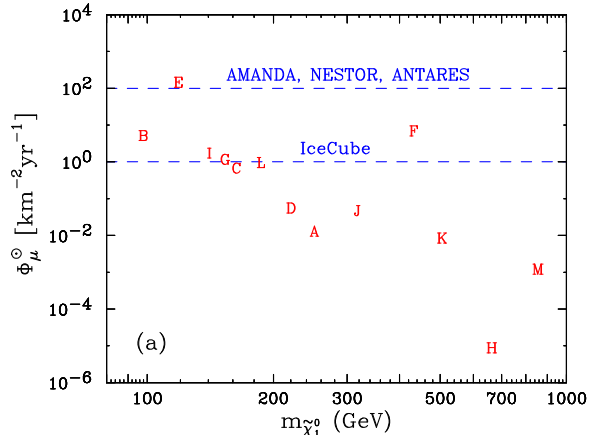


Figure 10. The recent discovery by the IceCube Collaboration of muons due to energetic neutrinos from the Sun can easily be accommodated in a number of scenarios with extra fermionic dimensions.

As seen in Fig. 11, these IceCube-friendly scenarios predict that a signal should be seen in the GENIUS detector now under construction¹¹. We are all on tenterhooks to see whether some supersymmetric interpretation of the IceCube dark-matter signal will be confirmed. It will also be vital to check whether the strength of this signal is compatible with the LHC signal for sparticle production and the universal gravity-mediated scenario for supersymmetry breaking assumed in Figs. 10 and 11.

4. Neutrino Masses and Oscillations

Back at the first $\cos\phi$ meeting, we were glimpsing an emerging default option for neutrino phenomenology. We were becoming convinced^{12,13} that there were no light sterile neutrinos besides the three active species confirmed by LEP. Theorists expected their masses to be hierarchical, but there was no experimental evidence for this hypothesis. The atmospheric and solar experiments had told us that the corresponding mixing angles were near maximal, and suggested that atmospheric $\nu_\mu \rightarrow \nu_\tau$ mainly. We had only the Chooz and Super-Kamiokande upper limits on θ_{13} . Theorists expected the light-neutrino masses to be mainly Majorana in nature.

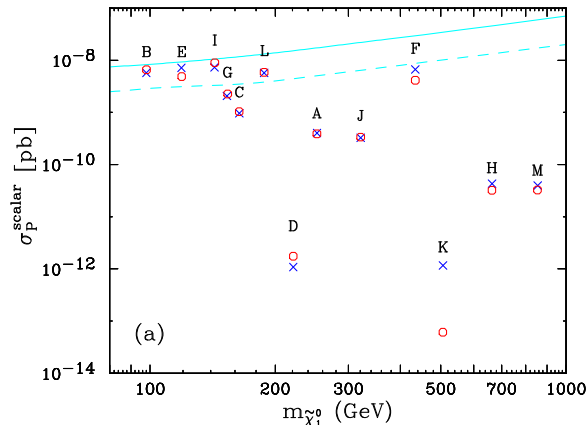


Figure 11. The IceCube-friendly scenarios in Fig. 10 tend also to predict rates for the scattering of dark-matter particles that may be accessible to direct detection.

It is also worth remembering that no experiment had actually confirmed a neutrino oscillation pattern, and some die-hards still advocated decay interpretations of the data, although theorists expected neutrino lifetimes much longer than the age of the Universe.

The neutrino-oscillation data raised almost as many questions as they answered. Could we really exclude light sterile neutrinos, as would certainly be required if the LSND claim were to be confirmed by MiniBooNE? Could we really exclude degenerate neutrino masses, or an inverse mass hierarchy? Although the LMA solution for solar-neutrino oscillations was strongly favoured after the first SNO neutral-current measurements, some die-hards were still clinging to the LOW and/or SMA solutions. Would τ production be observed, and would θ_{13} be accessible to the first generation of long-baseline neutrino experiments, a question vital for the detectability of CP violation in neutrino oscillations? Fundamentally, could the Majorana nature of neutrino masses be confirmed by neutrinoless double- β decay experiments, and/or the distinctive oscillation pattern be observed in long-baseline experiments?

Some of our questions were answered soon after $\cos^1 \phi$, and others more recently. The KamLAND experiment soon provided ample confirmation of the LMA solar solution¹⁴, and then MiniBooNE failed to confirm the LSND signal¹⁵. An unplanned bonus was the observation of supernova 2007b. Detailed measurements of its neutrinos, in particular in the reconstructed Super-Kamiokande detector, confirmed the favoured oscillation scenario. The MINOS experiment¹⁶ duly observed the expected oscillation pattern

in charged-current reactions, and the Gran Sasso experiments have observed τ production in the CERN beam ¹⁷. Most interesting has been the saga of θ_{13} . The combination of MINOS, ICARUS and OPERA found a hint that $\sin^2 2\theta_{13} \sim \text{few} \times 10^{-2}$. This indication was subsequently confirmed by the rejuvenated Super-Kamiokande experiment working in the first-generation off-axis JHF neutrino beam ¹⁸.

Thus, all the elements were in place for the recent approval of a fully-fledged neutrino factory. As you know, this should be able to answer our remaining questions about neutrino masses and oscillations, namely the hierarchy, degeneracy or inverse hierarchy of the mass spectrum, and the magnitude of the CP-violating phase δ . It will certainly pin down more precisely the magnitude of θ_{13} and measure the sign of Δm_{23}^2 via matter effects on the long-baseline beam. The best measurement of the CP-violating phase δ will be possible via the T -odd asymmetry:

$$P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) = 16s_{12}c_{12}s_{13}c_{13}^2s_{23}c_{23}\sin\delta \\ \times \sin\left(\frac{\delta m_{12}^2}{4E}L\right) \sin\left(\frac{\delta m_{13}^2}{4E}L\right) \sin\left(\frac{\delta m_{23}^2}{4E}L\right). \quad (1)$$

at the neutrino factory. The upgraded JHF beam and the Hyper-Kamiokande detector now under construction also have a good chance of making a preliminary measurement, and the combination of the two will be very useful for resolving ambiguities, as seen in Fig. 12 ¹⁹.

In addition to its ‘core business’ of long-baseline neutrino oscillation physics, the intense proton source of the neutrino factory will provide unique opportunities for other physics, including that using stopped or slow muons, which has been given considerable impetus by the recent results from PSI and BNL.

5. Discovery of Lepton Flavour Violation

Over the last decades of the 20th century, searches for the violation of charged-lepton flavours made steady but undramatic progress in pushing down the upper limits on observables such as $\mu \rightarrow e\gamma$ and $\mu \rightarrow e$ conversion on nuclei. This unspectacular hard work paid off in a big way with the recent discoveries of these two reactions at PSI and BNL ²⁰, respectively. The two measurements are very consistent, with the rate for $\mu \rightarrow e\gamma$ measured by MECO at BNL being a few per-mille of the branching ratio for $\mu \rightarrow e\gamma$, as expected in many models.

The violation of charged-lepton numbers was only to be expected at some level, once neutrino oscillations had been observed. However, the rates for such processes would have been negligible if there were no other

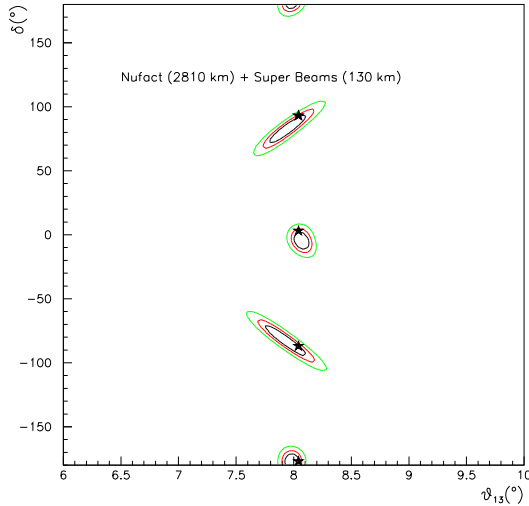


Figure 12. A combination of the measurements of the CP-violating neutrino phase by the superbeam and the neutrino factory will enable a precise determination of δ to be made.

low-energy particles beyond those in the Standard Model. The apparent observation of low-energy supersymmetry provides a good candidate for the new low-energy physics that enhances charged-lepton flavour violation. The minimal seesaw model for neutrino masses contains the following terms:

$$L_\nu = (Y_\nu)_{ij} (\nu, L)_i N_j H + \frac{1}{2} N_i M_{ij} N_j \quad (2)$$

where the N_i are three heavy singlet neutrino fields. The total number of physical parameters in this model is 18²¹. Nine of these are measurable in low-energy neutrino physics, namely 3 neutrino eigenmasses m_ν , 3 real mixing angles $\theta_{12,23,13}$, and 3 CP-violating phases - the oscillation phase δ and two Majorana phases $\phi_{1,2}$. The remaining 9 parameters are needed to describe the heavy-neutrino sector, and again include 3 heavy eigenmasses M_ν , 3 real mixing angles α and 3 CP-violating phases β . This minimal seesaw model therefore contains a total of 6 CP-violating phases, and the extra phases α control the rate for leptogenesis²², the favoured explanation for the origin of the baryon number of the Universe.

In the minimal supersymmetric extension of this minimal seesaw model, the soft supersymmetry-breaking parameters are renormalized by the Dirac

coupling matrix Y_ν :

$$\delta m_\ell^2 = -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)(Y_\nu^\dagger Y_\nu)_{ij} \ln\left(\frac{m_{GUT}}{m_{N_i}}\right), \quad (3)$$

$$\delta A_\ell = -\frac{3}{8\pi^2}Y_{\ell_i}(Y_\nu^\dagger Y_\nu)_{ij} \ln\left(\frac{m_{GUT}}{m_{N_i}}\right). \quad (4)$$

Non-diagonality in the neutrino Dirac couplings Y_ν in the mass eigenstate basis for the charged leptons induces lepton flavour violation in the slepton and sneutrino mass matrices, which depends on the mixing angles α and the CP-violating phases β that are not observable in low-energy interactions. This mechanism is certainly able to accommodate the MEG and MECO data, as seen in Fig. 13²³. It is certainly possible, even likely, that there are other sources of lepton flavour violation at the string and/or GUT scales, but this supersymmetric seesaw mechanism offers a ‘Standard Model’ to be confronted with the MEG, MECO and other data on the violation of charged-lepton flavours and CP.

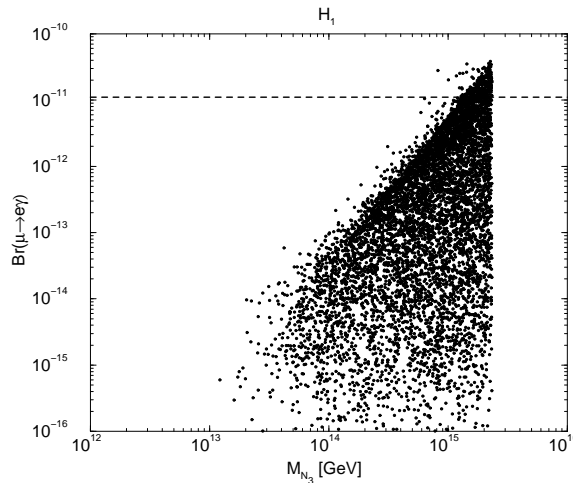


Figure 13. The recent discovery of $\mu \rightarrow e\gamma$ decay by MEG at PSI and the related discovery of $\mu \rightarrow e$ conversion on a heavy nucleus by the MECO Collaboration can easily be accommodated in the minimal supersymmetric seesaw model.

Examples of such processes include $\tau \rightarrow \mu\gamma, \tau \rightarrow e\gamma, \mu \rightarrow 3e, \tau \rightarrow 3\ell$ and the electric dipole moments of the electron and muon, which could have interesting rates in the minimal supersymmetric seesaw model, as seen in Fig. 14²³. Rumours have begun to circulate of interesting rare τ decays at the LHC, and also at the B factories following their recently completed

luminosity upgrades. Another interesting place to look for lepton flavour violation is in sparticle decays at the LHC or the e^+e^- linear collider. The suppression of rare $\mu(\tau)$ decays is in large part due to loop factors and the relatively large ratio of slepton over lepton masses, and relatively large branching ratios for $\chi_2 \rightarrow \chi \ell^+ \ell'^-$ are quite possible²⁴. Here again, some interesting hints have been emerging from the LHC, but we may have to wait for $\cos^{11} \phi$ and/or the LHC luminosity upgrade before these are confirmed.

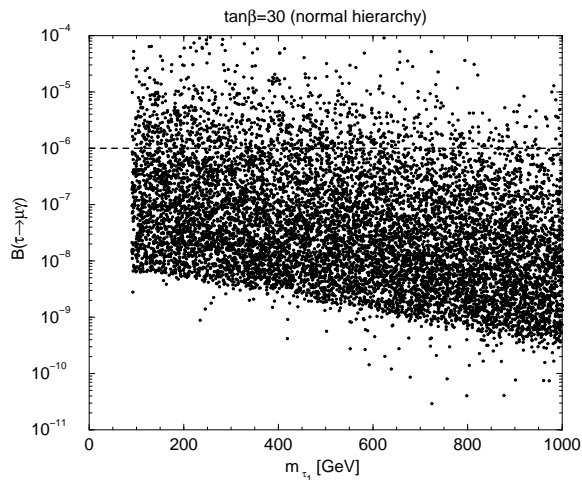


Figure 14. The discoveries of $\mu \rightarrow e$ processes by the MEG and MECO experiments increase the motivation that $\tau \rightarrow \mu\gamma$ may occur at a rate close the present experimental upper limit, as rumoured from the LHC and the B factories.

6. Space-Time Foam

We have known for over a decade now, thanks to the early experiments on the cosmic microwave background radiation, that the geometry of the Universe is flat on large distance scales. However, we have long expected that it should exhibit large quantum fluctuations on small distance and time scales:

$$\Delta E, \Delta\chi = O(1) \text{ in } \Delta x, \Delta t = O(1), \quad (5)$$

where the energy E , distance L and time t are measured in Planck units $\sim 10^{19}$ GeV, 10^{-33} cm and 10^{-43} s, respectively, and χ is a generic measure of space-time topology. The big question has been whether there could be any

observable consequences of this ‘space-time foam’ (5)? Most theorists have thought this must surely be impossible, but some disreputable characters have suggested that there might be observable loss of information across microscopic event horizons ^{25,26}, modifying the conventional superposition rules of quantum mechanics, and also that the ‘recoil’ of the vacuum during the passage of an energetic particle might modify its apparent velocity ²⁷:

$$c(E) = c_0 \left(1 - \frac{E}{M} + \dots \right), \quad (6)$$

where c_0 is the low-energy velocity of light and one might expect that the effective quantum-gravity scale $M \sim M_P$. This possibility first arose in the context of a string-inspired model of space-time foam ²⁸, but subsequently found possible in the more traditional loop approach to quantum gravity. Microscopic tests of quantum mechanics have not advanced much since the old days of CPLEAR ²⁹, over a decade ago, but there have been some interesting recent developments related to the suggestion (6).

Some of the best opportunities for probing this possibility are provided by astrophysical sources ³⁰: these offer long light propagation times $t = D/c$ and hence relatively large time delays $\delta t \sim (D/c^2)(E/M)$. Astrophysical sources with short intrinsic fluctuation time scales Δt yield the best figures of merit for probing the quantum-gravity scale M :

$$M \sim \frac{E \cdot D}{\Delta t}. \quad (7)$$

Examples of interesting astrophysical sources include gamma-ray bursters (GRBs), pulsars and active galactic nuclei (AGNs). Back at the beginning of the past decade, the latter already yielded limits ³¹

$$M > 2 \times 10^{16} \text{ GeV}, \quad (8)$$

and the GLAST collaboration had made preliminary estimates of their sensitivity to this possible quantum-gravity effect, as seen in Fig. 15 ³². Recently, we have started hearing rumours that GLAST observations of some GRBs exhibit unexplained time-lags ³³. It is in principle possible to distinguish propagation effects from time-lags at the sources, by looking for a correlation with distance D for GRBs with known redshifts z ³¹, and we look forward to hearing the results of such an analysis.

7. Probing the String-Particle Phase Transition

With the release of the maps of the cosmic microwave background (CMB) sky by the Planck satellite ³⁴, experimental tests of the string-particle phase transition have begun in earnest. Over a decade ago, it started dawning on

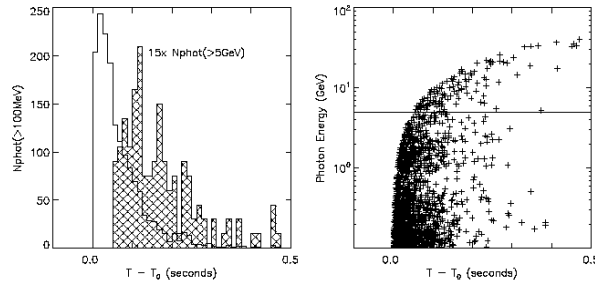


Figure 15. The dispersions in arrival times of energetic photons from gamma-ray bursters observed by the GLAST detector may be similar to simulations incorporating an energy-dependent velocity of light.

cosmologists that the CMB could be sensitive to trans-Planckian physics ³⁵, then string theorists got in on the action, and the rest, as they say, is history. Non-perturbative string phenomenology is now in full swing, with attempts to match the Planck polarization data, the apparent deviations from scale invariance and the indications of non-Gaussian behaviour of the CMB fluctuations.

One of the most interesting recent calculational developments has been the debut of lattice simulations of the string-particle transition and the emergence of space-time using the latest Petaflop computer Grids. We now know that there are many similarities between the behaviours of bulk quantities across this transition, such as the metric, and those in the corresponding quark-hadron transition, depicted in Fig. 16 ³⁶, which depend on the details of the string compactification.

8. Theoretical Advances

Who would have imagined back at the first $\cos\phi$ conference that we would be measuring directly the emergence of space-time from the string soup, and that we would be well on the way to calculating it? And who would have believed that we would now know how to calculate the present-day vacuum energy in terms of the soft supersymmetry-breaking parameters and the string vacuum moduli, as now seems ‘trivial’?

These and other remarkable developments have been made possible by the impressive theoretical advances since the first $\cos\phi$ conference. Thinking back to that meeting, the list of problems still unsolved then seems almost comical:

- The mechanism of supersymmetry breaking,
- Vacuum energy,

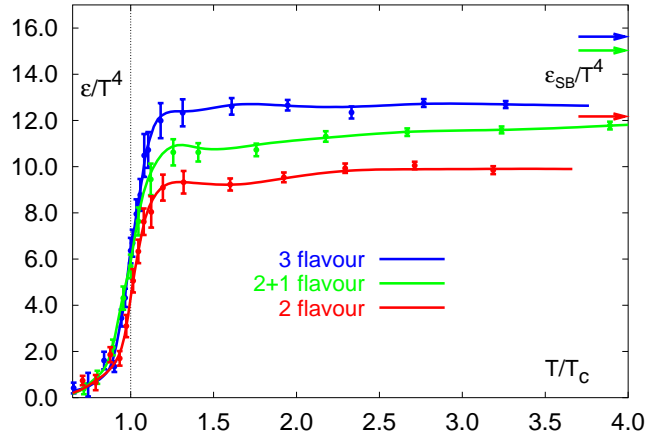


Figure 16. Recent simulations of the string-particle transition using Petaflop computer Grids indicate a behaviour analogous to that found for the quark-hadron phase transition, and have observable signatures in the cosmic microwave background radiation.

- How to fix the vacuum moduli,
- The cosmological gravitino problem,
- The supersymmetric CP-violating phases,
- The sizes of the extra dimensions,

and many more. This audience would be bored if I described how all these problems have been solved, and the margin of this proceedings contribution is any case too small. Here it suffices to say that *ABCDEFGHIJKLMNOPQRSTUVWXYZ* theory does indeed solve them, impossible as this might have seemed back before the $N > 2$ string revolutions, when our only theoretical tools were M , F and K theory.

Acknowledgements

I thank Alon Faraggi and Steve Abel for their foresight back in 2002, asking me to undertake this exercise in hindsight. No doubt my memory has become hazy on some points, and I apologize in advance to any 2012 readers for its comical lapses. They will probably consider many other discoveries to have been more exciting. Finally, I think the Yukawa Institute in Tokyo for its hospitality while writing up this load of crystal ball.

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