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Collider Physics

Bringing the heavens down to Earth

Recent developments and discoveries in astrophysics, particle physics and cosmology are creating an increasing synergy between astroparticle physics and particle physics at accelerators, as Nikolaos Mavromatos and James Pinfold explain.

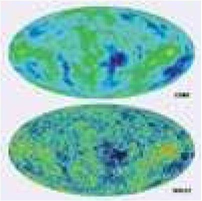

Figure 1

As announced a year ago now, the Wilkinson Microwave Anisotropy Probe (WMAP) has measured anisotropies in the cosmic microwave background radiation to an unprecedented accuracy of 10^{-9} K. The vastly improved precision of these data, compared with the groundbreaking results of the earlier Cosmic Background Explorer (COBE) satellite, is clearly shown in figure 1. This is opening up a new era for astroparticle physics, as the accuracy of the WMAP data has allowed a determination of cosmological parameters that are of relevance to particle physicists. Specifically, data from WMAP have significantly constrained the dark-matter content of the universe. This in turn strongly implies model-dependent and stringent constraints on models in particle physics, especially in minimal supersymmetry. In addition, the current evidence for an accelerating universe has revealed a massive component of "dark energy" in the total energy of the universe. One can imagine a pie graph showing the breakdown of the energy budget of the cosmos: 4% ordinary matter, 23% dark matter and 73% dark energy.

Other examples of the interplay between accelerator physics and astroparticle physics are provided by the following areas: extra dimensions and mini-black-hole production; neutrino oscillations; electroweak baryogenesis; dark matter consisting of the lightest supersymmetric particle (LSP); magnetic monopole production; and ultra-high-energy cosmic rays (UHECR).

The new collider experiments, in particular at the Large Hadron Collider (LHC) at CERN, offer the unique possibility of exploiting the significant links between astrophysics and particle physics. Importantly, there are some astrophysical scenarios that can be tested decisively at high-energy colliders. In other cases input from collider experiments is required to sharpen predictions for future astroparticle physics experiments, for example: the LSP detection rate, the UHECR spectrum in "top-down" models, and the understanding of very-high-energy hadronic interactions. Alternatively, cosmic-ray astrophysics may point the way to new physics at accelerators.

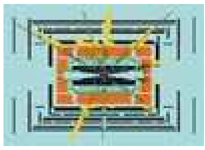

Figure 2

In theories with large extra dimensions at sub-millimetre distances, for example, and/or high energies of the order of 1 TeV or more, gravity may become a strong force. Thus, hypothetically, the energy required to produce black holes is well within the range of the LHC, making it a "black-hole factory". As Stephen Hawking has taught us, these mini black holes would be extremely hot little objects that would dissipate all their energy very rapidly by emitting radiation and particles before they wink out of existence. The properties of the Hawking radiation could tell us about the properties of the extra spatial dimensions, although there are still uncertainties in the theory at this stage. Nevertheless, astroparticle and collider experiments should provide useful input to the theoretical work in this area. Indeed, the signatures are expected to be spectacular, with very high multiplicity events and a large fraction of the beam energy converted into transverse energy, mostly in the form of quarks/gluons (jets) and leptons, with a production rate at the LHC rising as high as 1 Hz. An example of what a typical black-hole event would look like in the ATLAS detector is shown in figure 2.

If mini black holes can be produced in high-energy particle interactions, they may first be observed in high-energy cosmic-ray neutrino interactions in the atmosphere. Jonathan Feng of the University of California at Irvine and MIT, and Alfred Shapere of the University of Kentucky have calculated that the Auger cosmic-ray observatory, which will combine a 6000 km^2 extended air-shower array backed up by fluorescence detectors trained on the sky, could record tens to hundreds of showers from black holes before the LHC turns on in 2007.

Crossing the divide

Neutrino astrophysics has also provided us with exciting new results on neutrino masses and has opened up another area of synergy between particle physics, astrophysics and cosmology. The Sudbury Neutrino Observatory and Super-Kamiokande detectors have shown that neutrinos oscillate into other flavours. The result is final: the minimal Standard Model is dead, as it predicted vanishing neutrino masses and thus separately conserved lepton numbers. This is an existence proof that astroparticle-physics experiments can indeed produce results that have a fundamental impact on accelerator-based particle physics.

Another area with important cosmological implications is the violation of discrete symmetries C (charge), P (parity) and T (time reversal), and their combination CPT, which may be violated in some models of quantum gravity. Such issues are associated with explanations of the observed matter-antimatter asymmetry in the cosmos. Neutrino factories could provide answers to such fundamental questions. There is also the possibility for direct detection of massive isosinglet neutrinos at the LHC, the existence of which would have an important astrophysical impact. No doubt the synergy between neutrino astroparticle physics and accelerator-based neutrino physics will continue to yield possibilities for more vital insights.

The current generation of collider experiments and in particular the LHC project at CERN offer the unique possibility to perform precise measurements of the properties of the hadronic interaction. The motivation is that very-high-energy particles will have central importance in future studies of cosmic-ray physics. Measurements that are possible only at the LHC will have the potential to improve significantly the quality of measurements of cosmic-ray air showers both in the "knee" region and especially for the very highest energies at the "ankle" and beyond (see figure 3). The Tevatron collider at Fermilab provides hadron collisions at a centre-of-mass energy approaching 2 TeV, which is equivalent to a cosmic ray with an energy of about 2 PeV (2000 TeV) colliding with a stationary proton. Brookhaven’s Relativistic Heavy Ion Collider using nitrogen beams provides energies equivalent to that of a 5 x 10^{14} eV nitrogen nucleus incident on the atmosphere. The LHC will provide energies equivalent to roughly 10^{17} eV incident on a stationary proton. As can be seen from figure 3, these machines cover some of the important features of the cosmic-ray energy spectrum. It is worth noting that the energy flow in cosmic-ray air showers is within a few degrees of the incident particle - in effect the "beamline" - so it is vital that the LHC detectors have adequate forward detector systems.

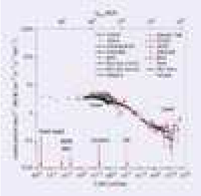

Figure 3

New physics

Over the years cosmic-ray experiments have reported a remarkable spectrum of anomalies, observed at regions of pseudo-rapidity outside the range of existing accelerator observations. The class of inclusive phenomena include anomalous examples of mean free path or long flying component, heavy flavour production, attenuation of secondary hadrons, and the energy fraction of air showers in emulsion-chamber families. There are also anomalous individual exotic events, which contain unexpected features: Centauro and anti-Centauro events; Chirons and halo events; and muon bundles. While these anomalies could be due to "unrecognized" Standard Model physics or an incorrect interpretation of the measurements, they could also be harbingers of new physics that would be manifest at the LHC and other future colliders. In 1971 K Niu and co-workers at Tokyo University, using balloon-borne emulsion chambers, reported evidence for decaying hadrons with unusual properties. After the discovery of charm in 1974, Tom Gaisser and Francis Halzen showed that the particles were in fact D-mesons; by then accelerator experiments had confirmed Niu’s measurements of mass, lifetimes and other properties.

Another recent example of the use of timely astroparticle experiments to guide our search for new physics at future colliders is provided by the development of new detectors such as the satellite-based Gaseous Antiparticle Spectrometer. Proposed to search for cosmic antimatter, this could also probe for supersymmetric dark matter up to a neutralino mass of approximately 400 GeV. This would extend the range of immediate future terrestrial direct dark-matter searches such as the GENIUS (germanium detectors in liquid nitrogen in an underground setup) experiment at the Gran Sasso Laboratory.

The LHC will make available large underground detectors such as ATLAS and CMS with an unprecedented area of fine-grained detectors and magnetic field volume. Following in the footsteps of the COSMOLEP experiment at CERN’s Large Electron Positron collider, these detectors could be used to determine precisely the direction and momentum of large numbers of penetrating cosmic-ray tracks within a very small area. One benchmark cosmic-ray phenomenon that can be studied is that of muon bundles, and another class of phenomena that can be studied in this way are upward-going showers, presumably from high-energy neutrino interactions in the Earth. In principle, trigger rates from the cosmic-ray phenomena mentioned above are low enough that they can be run in conjunction with standard trigger menus. In this way collider-physics experiments can make a direct contribution to astroparticle-physics experimentation.

In the "no man’s land" just beyond the frontiers of our knowledge nothing is certain, and most of the recent discoveries, which must often be interpreted in a model-dependent way, are subject to interpretation and debate. For instance, the evidence for a dark-energy content of the universe, its origin and precise nature (i.e. is it a cosmological constant, a quintessence field or something else?), the nature of dark matter, the nature of the UHECR, the existence of supersymmetry or other new physics, the possibility for the existence of large extra dimensions, etc, are issues that are still not resolved. The synergies between particle physics, astrophysics and cosmology in the next 10 years should amplify our ability to make faster and deeper inroads in all of these areas. There is no doubt that a new frontier for fruitful collaboration is now before us.

Further reading

A website that provides online resources for those exploring the common issues of collider physics (based on the ATLAS detector) and astroparticle physics has been created at http://csr.phys.ualberta.ca/astroATLAS/index.htm. Most of the references used to prepare this article can be found on the site.

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