2.8 Theoretical Physics

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Many research results were obtained in the theory group this year, in a wide variety of areas. Below is a selection of some of these results.

Supersymmetry and supergravity
A major branch of this year's research has continued to be supersymmetry (SUSY) and supergravity in four dimensions, and the link to ten-dimensional string theory, which offers a consistent theory of quantum gravity coupled to matter. One particular focal point is N=2 extended supersymmetry: the additional SUSY, twice as much as in the Minimal Supersymmetric Standard Model (MSSM), is the maximal amount where one has separate matter multiplets involving spin-0 and spin-½ fields and gauge multiplets, which also include spin-1 fields. We characterised the conditions required for fully supersymmetric vacuum configurations of these multiplets. This is important for so-called BPS black holes in supergravity. There, the matter fields near the event horizon prefer to be fully supersymmetric configurations related to the black hole charge and similar quantities. We also developed new techniques in superspace, where supersymmetry is nothing but a translation in a fictitious dimension, to describe the couplings of these matter multiplets.

While interesting on its own merits, extended four-dimensional supersymmetry is also related to compactifications from higher dimensions. For example, when ten dimensional string theories are compactified on a six-dimensional Calabi-Yau manifold, the resulting four dimensional theory exhibits N=2 supersymmetry, and the couplings of the vector multiplets reflect the geometry of the Calabi-Yau. To understand this better, we have proposed a relation between the free energy of simpler topological string theories compactified on a Calabi-Yau and the effective supergravity action, using the language of special geometry and a mathematical object called the Hesse potential.

A unique possibility occurs when taking supersymmetry to its maximal N=8 version: there is only a single multiplet involving the graviton, 28 spin-1 fields, and 70 spin-0 fields. We identified the conditions under which this supergravity admits deformations that leave the gauge group unaffected, but modify the gauge field sector, leading to families of models that appear similar but whose physical properties can drastically differ depending on the deformation.

String theory may also lead to a 4D world with only N=1 supersymmetry. We analysed N=1 *STU* supergravity models arising from string theory, both from a 4D (bottom-up) perspective and a 10D (top-down) perspective. Working directly in four dimensions has the advantage of circumventing the 10D Einstein's equations. We identified the effects of Kaluza-Klein monopoles, magnetic charges in lower dimensions from gravitational configurations in higher dimensions.

We also explored the connection to theories in two dimensions. After deforming a 4D theory with a certain surface operator in the field theory, we showed how an interpretation is possible as a 4D gauge theory coupled to a 2D N=(2,2) theory. The exact partition functions of both these 4D and 2D theories were computed and compared.

Feynman diagrams and gravitational lensing
The photons from the Cosmic Microwave Background (CMB) are deflected on their way to us by the gravitational effect of large scale structure in the universe. This gravitational lensing results in correlations in the CMB radiation that break statistical isotropy. The Hu-Okamoto estimator exploits this to obtain an estimate for the gravitational potential φ from CMB data. Gravitational lensing has now been observed with a significance of more than 25 σ, and the power spectrum of φ is starting to be constrained.

We developed a new approach, based on Feynman diagrams, that allowed us to calculate the bias/noise of the Hu-Okamoto estimator up to $O(\varphi^4)$. Previous calculations had found an unusually large $O(\varphi^4)$ correction, that raised concerns about the convergence of the φ expansion. Our Feynman diagram approach made it easy to diagnose this as being due to a class of diagrams that only starts to contribute at this order. We also showed that a reorganisation of the φ expansion improves the convergence, and thus solves this problem.

Jets
There are many sources of soft hadronic activity in collisions at the LHC: soft radiation from the hard quarks/gluons that enter the primary hard collision, secondary collisions (multiple parton interactions), etc. These effects are modeled by Monte Carlo programs that simulate LHC collisions. We scrutinised this modeling, by working out the features that are rigorously predicted by quantum field theory and comparing to the Pythia and Herwig Monte Carlo programs.

As an example, we looked at the invariant mass of jets in Z + jet and Higgs + jet events. The main effect of soft hadronic activity is captured by a single parameter Ω, describing the shift of the jet mass spectrum. Focussing on the effect of hadronisation, field theory predicts that Ω^{had} does not depend on transverse momen-

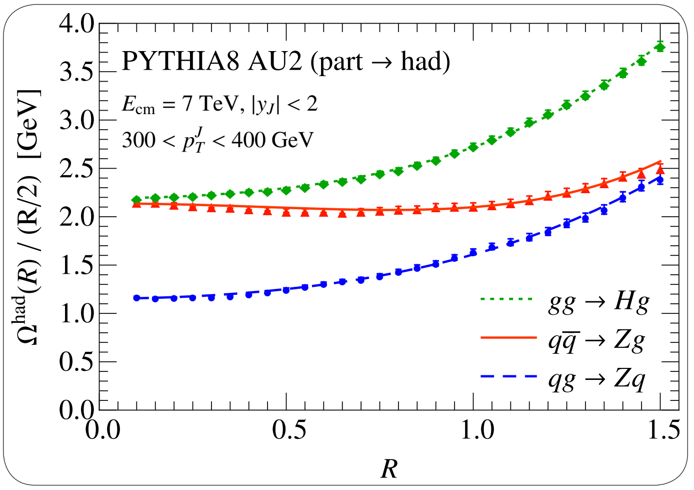

Figure 1. The jet radius R dependence of the hadronisation correction Ω^{had} to jet mass in Pythia. Ω^{had} behaves linearly at small R and only depends on whether the jet is initiated by a quark (blue dashed) or gluon (red solid and green dotted), in agreement with our field theoretic predictions.

tum or direction of the jet. However, Ω^{had} does depend on the jet radius R. For small R it scales linearly with R and only depends on whether the jet is initiated by a quark or gluon. Pythia and Herwig agree well with these features, see Fig. 1. On the other hand, there seems to be a degeneracy in Pythia and Herwig between multiple parton interactions and perturbative soft radiation associated with the primary collision. We showed that this degeneracy can be lifted by using the predicted dependence on the jet transverse momentum.

Self-interacting dark matter

The structure of our universe at galactic and subgalactic scales may be the key in unravelling the nature of dark matter. The canonical paradigm of collisionless cold dark matter has been extremely successful in explaining the structure of our universe in galaxy-cluster and larger scales. However, at galactic and subgalactic scales, the observed patterns of gravitational clustering deviate from the predictions of collisionless cold dark matter simulations; the latter predict very rich clumping of matter and too dense galactic centers. The discrepancies between simulations and observations suggest that a shift in the dark-matter paradigm may be needed. Self-interacting dark matter has emerged as a compelling alternative to collisionless cold dark matter. If the dark-matter particles scatter off each other inside haloes, then the redistribution of energy and momentum can heat up the low-energy material, smooth overdensities and suppress the star-formation rate, thus bringing theory in better agreement with observations.

This paradigm shift points to particle-physics models that are quite different from the scenario involving Weakly Interacting Massive Particles (WIMPs). Various aspects of dark-matter physics along this new direction were explored. The dark-matter self-scattering cross-section per unit mass required to affect the dynamics of haloes is around $\sigma_{scatt}/m_{DM} \sim 1$ barn/GeV, which far exceeds the weak-scale cross sections. This value suggests that dark matter couples directly to a new light force mediator. Sizeable couplings to light force carriers typically also imply large annihilation cross sections. This is well accommodated within the asymmetric dark matter scenario, in which the dark-matter relic abundance is due to an excess of dark particles over dark antiparticles that cannot be destroyed, independently of how large the annihilation cross section may be. A novel mechanism for the generation of particle-antiparticle asymmetries via CP-violating scatterings was investigated. Exploring the low-energy phenomenology of self-interacting asymmetric dark matter, including the effect on the dynamics of haloes, presupposes understanding the cosmology of these models, which can be quite complex. It may involve the formation of dark-matter bound states, and the late kinetic decoupling of dark matter from dark radiation. The role of such bound states in dark-matter physics was explored.