Research Statement

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All reference numbers correspond those in the publication list in my curriculum vitae.

1 General Research Interests

My research interests lie in the field of high-energy particle physics and particle cosmology. I am particularly interested in investigating the nature and properties of the non-baryonic component of the dark matter which overwhelming evidence suggests composes nearly a quarter of the energy budget of our universe. Within the last few years, data from the LHC, from observational astronomy, and from dark-matter direct-detection experiments have significantly constrained what the properties of that dark matter might be. However, these experimental results do not yet point unambiguously toward a single coherent picture of the dark sector. On the contrary, a tantalizing but at the same time inconclusive and often seemingly contradictory set of data anomalies, combined with the absence of any signal for physics beyond the Standard Model at the LHC, has prompted a reevaluation of traditional assumptions about the dark sector and has motivated novel, non-traditional approaches to the dark-matter problem.

One of my primary aims is therefore to examine the dark-matter question from as broad a perspective and within as general a framework as data allow. This means considering the full range of viable possibilities for addressing the dark-matter question — especially those possibilities which challenge some of the fundamental assumptions about the nature and properties of the dark matter. In addition, it also means considering the phenomenology and cosmology consequences of the dark sector as a unified whole, rather than focusing on the particles within that sector which provide the majority of the present-day dark-matter relic abundance alone.

A wide variety of considerations provide valuable information on the properties of the dark sector. Consequently, my research is intimately tied to a broad variety of topics in particle astrophysics, cosmology, model-building, formal theory, and collider phenomenology. Indeed, given the wealth of information which the LHC has already provided and will continue to provide over the coming years, this last topic has played and will no doubt continue to play a significant role in my investigation of the dark-matter question and how this question could potentially tell us more broadly about fundamental physics at high scales.

2 General Dark Sectors and Dynamical Dark Matter

In Refs. [7, 6], collaborator Keith Dienes (Arizona) and I proposed dynamical dark matter (DDM) as a more general way of thinking about the dark-matter problem which does not presuppose dark-matter stability. In a scenario in which such stability is not assumed, this problem can be interpreted as a tension between competing constraints on the lifetimes and cosmological abundances of particles which contribute to the dark-matter relic density. On the one hand, WMAP results suggest that cold dark matter contributes a substantial fraction $\Omega_{\rm DM} \approx 0.23$ of the energy density in our universe. On the other hand, observational limits imply a bound on the lifetime of any typical dark-matter candidate with a relic abundance which is roughly 10^9 times the present age of the universe. In traditional dark-matter scenarios, such "hyperstability" is the only way in which these competing constraints on lifetimes and abundances can be satisfied.

By contrast, the DDM framework offers an alternative paradigm for reconciling these competing constraints within the context of a more general dark sector. In particular, the dark-matter candidate in DDM scenarios is not a single, hyperstable particle, but rather an ensemble comprising a vast number of individual constituent fields with different lifetimes and cosmological abundances. For such a dark-matter candidate, consistency with experimental limits is arranged not by imposing hyperstability, but rather by balancing the lifetimes of these constituents against their abundances across the ensemble as a whole. In Ref. [7], we explored many of the cosmological consequences of DDM ensembles which result from the ongoing decays of their constituent fields. One such consequence is that the total dark-matter relic abundance, the distribution of that total abundance across the ensemble, and even the dark-matter equation of state exhibit a non-trivial time dependence beyond that associated with the background cosmology. We obtained general expressions for these quantities and derived constraints on the scaling relations between constituent lifetimes and abundances across the ensemble. Moreover, we showed that the correct scaling relations arise naturally in theories in which the constituent fields of the DDM ensemble are the KK excitations of a neutral scalar field propagating in the bulk of extra spacetime dimensions. This implies that theories involving extra dimensions, and by extension string theory, naturally give rise to DDM ensembles. Moreover, in Ref. [6], Keith Dienes and I furnished an explicit example of a viable DDM ensemble in this context. In Ref. [3], we examined the phenomenological, astrophysical, and cosmological constraints on this explicit DDM model and demonstrated that all of these constraints can simultaneously be satisfied.

Not only are DDM ensembles interesting from a cosmological perspective, but they also give rise to a variety of characteristic experimental signatures which can help to distinguish them from traditional dark-matter candidates. For example, at the LHC, they can give rise to measurable differences in the kinematic distributions of visible-sector fields produced alongside the ensemble constituents via the decays of other, heavier particles. In Ref. [2] Keith Dienes, Shufang Su (Arizona), and I investigated the potential for distinguishing DDM ensembles on the basis of characteristic features in the invariant-mass distributions of pairs of hadronic jets produced in this manner. We demonstrated that once an initial excess of events is observed it should be possible to distinguish a broad class of DDM ensembles on the basis of such distributions at the 5σ significance level within the first year of running at the upgraded LHC. We are currently investigating additional techniques for distinguishing DDM ensembles on the basis of collider kinematics.

Dark-matter direct-detection experiments provide another context in which DDM ensembles give rise to characteristic signatures which differ from those associated with traditional dark-matter candidates. In particular, in Ref. [1], Keith Dienes, Jason Kumar (Hawaii), and I studied the effect of replacing a traditional dark-matter candidate with a DDM ensemble on the energy spectra of nuclear-recoil events observed at dark-matter detectors. We demonstrated that even in the simplest case in which elastic scattering dominates the contribution to the recoil-event rate for all relevant ensemble constituents, such a replacement can give rise to a substantial deviation in the shape of the observed recoil-energy spectrum. Moreover, we showed that in many cases, such a deviation could be observed at the 5σ significance level at the next generation of direct-detection experiments. We are currently studying to what extent these deviations can be distinguished from those associated with other modifications of the standard dark-matter paradigm.

3 Dark Matter and Fundamental Physics at the LHC

In addition to my work on dynamical dark matter, I am also interested more broadly in what can LHC data can tell us about the properties of the dark sector. In a broad class of new-physics scenarios, dark-matter particles can be produced by the decays of additional, heavy fields in the theory which are charged under the Standard Model $SU(3)$ gauge group and can therefore be produced copiously and the LHC via strong interactions. If these fields and the fields of the dark sector are both charged non-trivially under the same exact or approximate symmetry, the decay chains initiated by these heavy fields will invariably include one or more dark-sector fields. These dark-sector fields typically manifest themselves in the detector in the form of missing transverse energy. Beyond that, however, the decay phenomenology of these heavy, strongly-interacting fields is highly model-dependent. Thus, the optimal strategy for identifying signals of new physics in scenarios of this sort is often far from obvious.

One interesting class of such scenarios is that in which the heavy fields preferentially decay to final states including large numbers of top quarks. Such "top-rich" scenarios give rise to characteristic event topologies featuring large numbers of hadronic jets and substantial missing transverse energy. In Ref. [4], Joseph Bramante (Hawaii), Jason Kumar, and I examined the prospects for observing a signal of new physics using a search strategy particularly relevant for top-rich scenarios. This strategy involves focusing on the purely hadronic channel and selecting signal events primarily on the basis of the total missing transverse energy and the number of isolated energetic jets in the event. We demonstrated that in a variety of top-rich scenarios, this search strategy provides a comparable or better discovery potential than that afforded by alternative strategies.

In addition to investigating the implications of missing-energy signatures, I am also interested in examining more broadly what LHC data can tell us about how the dark sector is embedded within the ultraviolet theory which ultimately must subsume both dark and visible sectors at high scales. For example, in many new-physics scenarios, the dark-matter candidate and any new strongly-interacting particles are united as part of a sector of fields charged under some additional exact symmetry. Indeed, in such scenarios, it is this same symmetry which ensures the stability of the dark-matter candidate. Signatures of heavy, strongly-interacting exotics which decay to final states which do *not* include invisible particles (and hence substantial missing energy) therefore tell us a great deal about the symmetry structure of the underlying ultraviolet theory. By extension, they also provide insight into how the dark sector is embedded within the context of that theory.

One promising channel in which such signatures can arise is that involving six energetic jets and no substantial missing energy. This event topology arises in scenarios (such as R-parity-violating supersymmetry with a light gluino) in which the heavy, strongly-interacting fields are pair-produced, and each subsequently decays predominately into final states comprising three Standard-Model quarks or gluons. In Ref. [5], Jason Kumar, Arvind Rajaraman (UC Irvine), and I conducted a detailed, model-independent analysis of the LHC phenomenology of this detection channel. In particular, we identified the combinations of Lorentz and $SU(3)$-color representations which permit such a decay phenomenology and examined the LHC discovery reach for each combination. The results of this study can therefore have important consequences for the interpretation of any observed excess in this channel.

4 Other Research Interests

In addition to dark-matter physics, my research interests extend over a broad range of additional topics in particle theory and phenomenology. My work in these other areas, some of it ongoing, is not only satisfying for its own sake, but also has informed — and continues to inform — my investigation of the dark-matter puzzle.

One subject on which I have worked extensively is extensions of the Standard Model with additional scalar $SU(2)$ doublets. In Ref. [14], Shufang Su and I examined the collider phenomenology of a two-Higgs-doublet model in which one doublet couples to both up- and down-type quarks, while a separate doublet couples only to leptons. On a related topic, in Ref. [18], we studied the detection prospects for a light Higgs boson produced in association with a pair of top quarks and decaying to a pair of muons, both in the Standard Model and in theories with enhanced Higgs couplings. In Refs. [13, 10], with collaborators Ethan Dolle (Arizona) and Xinyu Miao (Arizona), we studied several aspects of the LHC phenomenology of models with an additional, "inert" scalar doublet which is prohibited by symmetry from coupling to any of the Standard-Model fermions. This work in Higgs physics has given me a firm grounding in collider phenomenology and a fluency with the analysis techniques and simulation tools used in the field.

In addition to these phenomenological pursuits, I have also engaged in more theoretical work in model-building and formal theory, much of it in the context of supersymmetry. In Ref. [11], Keith Dienes and I examined several issues related to whether supersymmetric theories with non-zero Fayet-Iliopoulos terms may be consistently coupled to supergravity. In Refs. [17, 16], we examined the vacuum structures of supersymmetric theories and identified several novel features relevant for supersymmetry-breaking. In Ref. [17], we presented a simple construction in which metastable vacua occur at tree-level, and in which supersymmetry-breaking is sourced by both D-terms and F-terms. All relevant dynamics is perturbative, and hence calculations of ground-state energies and vacuum-transition rates can be performed explicitly. In Ref. [16], we presented a class of models which give rise to another novel feature: towers of metastable vacua. We studied the instanton-induced tunneling dynamics associated with such vacuum towers and examined the different vacuum-decay patterns to which they give rise. These more formal pursuits have also proven valuable for my work as a phenomenologist and as a dark-matter theorist.

In the future, I hope to continue to broaden my perspective by continuing to pursue research interests of this more general sort in addition to dark-matter physics.

5 Future Directions

Over the coming decade, new data from the LHC and from other direct or indirect probes of the dark sector (including XENON1T, SuperCDMS, Fermi-LAT, Planck, and AMS-02) will continue to enrich our knowledge and reshape assumptions about dark matter. During such a vibrant era, I hope to continue exploring the dark-matter problem within the most general context possible. Indeed, many of the most intriguing phenomenological possibilities inherent within the dynamical dark-matter framework remain to be explored, as do many of the cosmological consequences of a non-minimal dark sector. In addition, the LHC may also soon provide us with a wealth of information not only about the dark sector, but also about the full ultraviolet theory into which both dark and visible sectors are subsumed. Thus, I also hope to continue exploring strategies for uncovering new physics at colliders and to continue investigating the implications of LHC data more broadly for physics at high scales. Moreover, I am always interested in broadening my horizons as a particle theorist and look forward to taking advantage of the joint interest of future colleagues, both in these research areas and others, in exploring what information can be extracted from forthcoming experimental data about the nature of our universe at high scales.