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Beyond the Standard Model: The Weak Scale, Neutrino Mass and the Dark Sector

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1 Summary

The goal of this proposal was to advance theoretical studies into questions of collider physics at the weak scale, models and signals of dark matter, and connections between neutrino mass and dark energy. The project was a significant success, with a number of developments well beyond what could have been anticipated at the outset. A total of 35 published papers and preprints were produced, with new ideas and signals for LHC physics and dark matter experiments, in particular. A number of new ideas have been found on the possible indirect signals of models of dark matter which relate to the INTEGRAL signal of astrophysical positron production, high energy positrons seen at PAMELA and Fermi, studies into anomalous gamma rays at Fermi, collider signatures of sneutrino dark matter, scenarios of Higgs physics arising in SUSY models, the implications of galaxy cluster surveys for photon-axion conversion models, previously unconsidered collider phenomenology in the form of "lepton jets" and a very significant result for flavor physics in supersymmetric theories. Progress continues on all fronts, including development of models with dramatic implications for direct dark matter searches, dynamics of dark matter with various excited states, flavor physics, and consequences of modified missing energy signals for collider searches at the LHC.

2 Goals and Accomplishments

The overarching goal of this project was to develop and study theories that had connections to dark sector physics (focusing on, but not limited to, dark matter, neutrino physics, and dark energy). In doing so, the hope was that connections might be made between collider signals, astrophysical signals, and possible signals in underground experiments. A wide variety of developments were made in understanding models of dark matter, relating different experiments in model independent ways, understanding how fluxes of cosmic rays can be enhanced and the collider signals that are associated with them.

2.1 Indirect Detection of Dark Matter and Connections to Colliders

The INTEGRAL observation of excess positron production in the galactic center has motivated the consideration of dark matter models that can produce large numbers of low-energy ($\sim$ MeV) positrons, without too much associated high energy radiation. One proposal is by Finkbeiner and Weiner (Physical Review D **76**, 2007), that the dark matter has an excited state which decays via e^+e^- emission. With high concentrations of dark matter in the central part of the galaxy, collisions between the WIMPs can cause excitations which lead to positrons, in accordance with the existing signal.

A generic feature we found of these models was the need for a relatively long-range force in the dark sector, mediated by a light ($\sim$ GeV) particle. The consequence of this is a new mode for dark matter annihilation, with resultant implications for indirect detection searches. With Ilias Cholis and Lisa Goodenough (both supported, in part, by this grant), we performed studies of the positron production in the galaxy from dark matter annihilation. Because of the new annihilation channel, dramatically different positron spectra were possible compared with previous studies, and rates much more relevant for PAMELA, the current cosmic ray experiment, were achievable. We studied that implications of the synchrotron radiation for the WMAP "haze" (see Finkbeiner, Astrophysical Journal **614** 2004), and found that achieving a significant haze component was generally associated with significant signals at PAMELA.

The PAMELA results appeared in late 2008, confirming the predictions of this setup, which motivated a paper (Arkani-Hamed et al 2009) which synthesized all the basic ideas, put the framework onto a more solid theoretical ground, and developed how the same light mediator could lead to an enhanced annihilation rate beyond what was expected for a standard thermal WIMP. In a number of papers, this was followed up, studying the actual signals at PAMELA and Fermi, with the most recent result (Finkbeiner et al 2010) combining issues of relic abundance, needed interaction rates, mass scales, and other issues to find genuine points in parameter space that fit the ensemble of data. Future studies on this will continue, but in particular signals from Planck should clarify this matter.

One of the most exciting consequences of this model was the collider signals of the model. In particular, in a recent paper (Arkani-Hamed & Weiner, 2009) we argued that the generic signal would be highly boosted sets of leptons, with low invariant mass and with possibly displaced vertices. These objects were termed "lepton-jets" and have become a completely new object of study in collider physics, involving studies at D0 and CDF already, planned studies at ATLAS and CMS, and even a proposed experiment (APEX) at JLAB. One of the principle goals of model building is to develop precisely these new, qualitative signatures to be looked for, and finding such a novel example is one of the great successes of this project.

2.2 Direct Detection of Dark Matter

Over the course of this project, a pair of interesting results motivated new work in direct detection studies. Specifically, the DAMA annual modulation signature persisted, while the CoGeNT experiment reported an excess of events at low energy, possibly consistent with a light WIMP. One of the aims of this project was to incorporate and study signals from dark matter experiments as they came in, and we produced a number of results on both of these fronts.

With regard to CoGeNT, in an early paper (Chang et al 2010), we studied the relative consistency of CoGeNT with other experiments, including DAMA, and what would be required to get agreement. We noted the different challenges and clarified the issues early on. More recently, this was extended (Fox, Liu and Weiner 2010) by developing techniques that could compare different experiments in a manner that was independent of astrophysical uncertainties. We showed that a number of tensions existed independent of any astrophysical assumptions, making it very unlikely that these signals were arising from elastically scattering dark matter.

A number of efforts have been made into a separate idea, that of inelastic dark matter. In this project, we updated the status of the iDM model shortly after the first DAMA/LIBRA release (Chang et al 2008), which helped clarify the status and what experiments coming online could be helpful. However, there was a great deal of theoretical work, including a study of the effects of realistic halos (as modeled by N-body simulations) (Kuhlen et al, 2009), studying the effects of streams in inelastic models (Lang and Weiner 2009), studying the effects of Thallium impurities in the DAMA experiment on the allowed parameter space (Chang, Lang and Weiner 2010) and the relevance of magnetic interactions being the dominant mediator (Chang, Weiner and Yavin 2010). This ensemble of work has clarified the status of the scenario, and how and what experiments should test this over the next year.

2.3 Collider Physics

One of the key elements that informs our expectations of collider physics signatures at the LHC is the very significant constraints placed by precision measurements on flavor changing processes such as kaon and B-meson oscillations, and transitions such as $b \to s\gamma$, $\mu \to e\gamma$, and $\tau \to \mu\gamma$ to name a few. The absence of anomalies in these areas has strongly motivated theories with flavor-blind new physics (for a review in the context of supersymmetry, see, e.g., Gabbiani, Gabrielli, Masiero, and Silvestrini, **NPB**477, 1996). Theories such as gauge mediation, minimal supergravity, gaugino mediation, among others, all offer scenarios with degenerate squarks and degenerate sleptons. With Graham Kribs and Erich Poppitz (Phys. Rev. D **78**, 2008), I have shown that theories with an enlarged R-symmetry are considerably safer from these effects than previous supersymmetric theories. Even theories with very large non-degeneracy and essentially no flavor symmetry are consistent within this new scenario. Such models have dramatically different predictions for collider physics, which have not been examined at all previously, due to the significant biases towards flavor-blind mediation.

Higgs physics has been another area of focus for the project. In particular, research has been focused on what Higgs scenarios would admit a Higgs boson lighter than the standard model limit of 114.4 GeV. Previous work with Fox and Chang (supported in part by this grant) focused on scenarios where the Higgs would decay into fully visible modes, but which were reconstructed with such low efficiencies that only weak limits could be set. The more recent work with Chang (JHEP **0805**, 2008) extends this line of research to scenarios with partially invisible modes as well. We reviewed available searches which would constrain such topologies and developed limits on these scenarios, finding they also viably can evade LEP limits. Such scenarios actually have more significant implications for other searches, as the invisible decay modes are often related to cascade decays of new particles in supersymmetric theories. The implications of this are being studied.

Because these developments in Higgs physics have become an important part of the discussion about Higgs limits in supersymmetric theories, the present state of experiment and theory was summarized with Chang, Dermisek and Gunion (Ann. Rev. Nucl. Part. Sci. **58**, 2008) in a paper prepared for Annual Reviews of Nuclear Science. We consolidated all existing searches, limits, and known topologies. This paper then provides a basis for phenomenologists attempting to understand the constraints and possibilities available for Higgs physics with decays beyond those of the standard model.

2.4 Dark Matter and Collider Physics - Other studies

One of the most important phenomenological consequences of dark matter is its implications for cascade decays at colliders. Because it is often at the bottom of cascade decays, its nature can be very important for the features of complicated cascades, which are ubiquitous in supersymmetric theories. With Thomas and Tucker-Smith (Phys. Rev. D **77**, 2008), we considered the implications of mixed sneutrino dark matter for collider searches. We focused on searches with leptons, in particular focusing on edges in opposite sign, same flavor (OSSF) dilepton searches. By considering the mass distributions, we demonstrated that the LHC should be capable of distinguishing mixed sneutrino dark matter in various regions of parameter space from neutralino dark matter. Additionally, we showed the recent proposals for lightest partner mass analyses of Cheng et al. were extendable to this scenario. These ideas may be very relevant if the DAMA claim of dark matter detection persists, as we will describe below.

2.5 Constraints on Dark Energy

Although high-redshift Type Ia supernovae provide the most immediate implications for dark energy and the expansion of the universe, the growth of structure is also an important result. Future cluster count surveys will be very important to further constraining the dark energy equation of state. With Erlich and Glover, we considered the implications of flux-limited cluster count surveys for models of dark energy, in particular photon-axion models of cosmic dimming. We demonstrated that the use of empirical luminosity-temperature measurements absorbed the effects of such dimming, allowing a direct extraction of the true dark energy equation of state. The development of these surveys will in the future serve as an independent check on dark energy, insensitive to the presence of any cosmic dimming mechanism.

3 Summary

The overarching goals of a phenomenology project are many: first, to develop new models that provide motivations to use existing data in new, and interesting ways; second, to consider confusing data, and attempt to understand how it might function in the context of reasonable particle physics models; third, to develop new models with qualitatively new signatures. This project has been successful in all three, having developed new scenarios for flavor, Higgs physics, dark matter, and cosmic ray signals. The proposal of "lepton jets" has provided a motivation for new analyses and even new experiments; the development of inelastic dark matter models has pushed broader analyses for direct detection experiments; models of dark matter with dark forces have changed the approach to thinking about cosmic ray data. In summary, the project exceeded the initial goals, both in quantitative output (i.e., number of papers), but also qualitatively, having helped push ideas of beyond the standard model physics forward, and producing ideas that continue to yield interesting avenues for research.

4 Publications and Preprints

1. **"Cores in Dwarf Galaxies from Dark Matter with a Yukawa Potential"**, A. Loeb and N. Weiner, arXiv:1011.6374 [astro-ph.CO]

2. **"Consistent Scenarios for Cosmic-Ray Excesses from Sommerfeld-Enhanced Dark Matter Annihilation"**, D. P. Finkbeiner, L. Goodenough, T. R. Slatyer, M. Vogelsberger and N. Weiner, arXiv:1011.3082 [hep-ph]

3. **"Integrating Out Astrophysical Uncertainties"**, P. J. Fox, J. Liu and N. Weiner, arXiv:1011.1915 [hep-ph], FERMILAB-PUB-10-437-T(2010)

4. **"Magnetic Inelastic Dark Matter"**, S. Chang, N. Weiner and I. Yavin, arXiv:1007.4200 [hep-ph]

5. **"Impure Thoughts on Inelastic Dark Matter"**, S. Chang, R. F. Lang and N. Weiner, arXiv:1007.2688 [hep-ph]

6. **"CoGeNT Interpretations"**, S. Chang, J. Liu, A. Pierce, N. Weiner and I. Yavin, JCAP **1008**, 018 (2010) [arXiv:1004.0697 [hep-ph]]

7. **"Peaked Signals from Dark Matter Velocity Structures in Direct Detection Experiments"**, R. F. Lang and N. Weiner, JCAP **1006**, 032 (2010) [arXiv:1003.3664 [hep-ph]]

8. **"Dark Matter Direct Detection with Non-Maxwellian Velocity Structure"**, M. Kuhlen *et al.*, JCAP **1002**, 030 (2010) [arXiv:0912.2358 [astro-ph.GA]]

9. **"MiXDM: Cosmic Ray Signals from Multiple States of Dark Matter"**, I. Cholis and N. Weiner, arXiv:0911.4954 [astro-ph.HE]

10. **"The Fermi Haze: A Gamma-Ray Counterpart to the Microwave Haze"**, G. Dobler, D. P. Finkbeiner, I. Cholis, T. R. Slatyer and N. Weiner, Astrophys. J. **717**, 825 (2010) [arXiv:0910.4583 [astro-ph.HE]]

11. **"Neutrino Mass, Sneutrino Dark Matter and Signals of Lepton Flavor Violation in the MRSSM"**, A. Kumar, D. Tucker-Smith and N. Weiner, JHEP **1009**, 111 (2010) [arXiv:0910.2475 [hep-ph]]

12. **"High Energy Electron Signals from Dark Matter Annihilation in the Sun"**, P. Schuster, N. Toro, N. Weiner and I. Yavin, arXiv:0910.1839 [hep-ph] SU-ITP-09-44(2009)

13. **“The Dark Side of the Electroweak Phase Transition”**, S. Das, P. J. Fox, A. Kumar and N. Weiner, JHEP **1011**, 108 (2010) [arXiv:0910.1262 [hep-ph]]

14. **“Momentum Dependent Dark Matter Scattering”**, S. Chang, A. Pierce and N. Weiner, JCAP **1001**, 006 (2010) [arXiv:0908.3192 [hep-ph]]

15. **“The Fermi gamma-ray spectrum of the inner galaxy: Implications for annihilating dark matter”**, I. Cholis, G. Dobler, D. P. Finkbeiner, L. Goodenough, T. R. Slatyer and N. Weiner, arXiv:0907.3953 [astro-ph.HE]

16. **“Inelastic Dark Matter and DAMA/LIBRA: An Experimentum Crucis”**, D. P. Finkbeiner, T. Lin and N. Weiner, Phys. Rev. D **80**, 115008 (2009) [arXiv:0906.0002 [astro-ph.CO]]

17. **“Capture and Indirect Detection of Inelastic Dark Matter”**, A. Menon, R. Morris, A. Pierce and N. Weiner, Phys. Rev. D **82**, 015011 (2010) [arXiv:0905.1847 [hep-ph]]

18. **“PAMELA, DAMA, INTEGRAL and Signatures of Metastable Excited WIMPs”**, D. P. Finkbeiner, T. R. Slatyer, N. Weiner and I. Yavin, JCAP **0909**, 037 (2009) [arXiv:0903.1037 [hep-ph]]

19. **“Cosmic Ray Positrons from Annihilations into a New, Heavy Lepton”**, D. J. Phalen, A. Pierce and N. Weiner, Phys. Rev. D **80**, 063513 (2009) [arXiv:0901.3165 [hep-ph]]

20. **“The Case for a 700+ GeV WIMP: Cosmic Ray Spectra from ATIC and PAMELA”**, I. Cholis, G. Dobler, D. P. Finkbeiner, L. Goodenough and N. Weiner, Phys. Rev. D **80**, 123518 (2009) [arXiv:0811.3641 [astro-ph]]

21. **“The PAMELA Positron Excess from Annihilations into a Light Boson”**, I. Cholis, D. P. Finkbeiner, L. Goodenough and N. Weiner, JCAP **0912**, 007 (2009) [arXiv:0810.5344 [astro-ph]]

22. **“Nuclear scattering of dark matter coupled to a new light scalar”**, D. P. Finkbeiner, T. R. Slatyer and N. Weiner, Phys. Rev. D **78**, 116006 (2008) [arXiv:0810.0722 [hep-ph]]

23. **“LHC Signals for a SuperUnified Theory of Dark Matter”**, N. Arkani-Hamed and N. Weiner, JHEP **0812**, 104 (2008) [arXiv:0810.0714 [hep-ph]]

24. **“A Theory of Dark Matter”**, N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer and N. Weiner, Phys. Rev. D **79**, 015014 (2009) [arXiv:0810.0713 [hep-ph]]

25. **“High Energy Positrons From Annihilating Dark Matter”**, I. Cholis, L. Goodenough, D. Hooper, M. Simet and N. Weiner, Phys. Rev. D **80**, 123511 (2009) [arXiv:0809.1683 [hep-ph]]

26. **“Using the Energy Spectrum at DAMA/LIBRA to Probe Light Dark Matter”**, S. Chang, A. Pierce and N. Weiner, Phys. Rev. D **79**, 115011 (2009) [arXiv:0808.0196 [hep-ph]]

27. **“Inelastic Dark Matter in Light of DAMA/LIBRA”**, S. Chang, G. D. Kribs, D. Tucker-Smith and N. Weiner, Phys. Rev. D **79**, 043513 (2009) [arXiv:0807.2250 [hep-ph]]

28. **“CMB and 21-cm Signals for Dark Matter with a Long-Lived Excited State”**, D. P. Finkbeiner, N. Padmanabhan and N. Weiner, Phys. Rev. D **78**, 063530 (2008) [arXiv:0805.3531 [astro-ph]]

29. **“High Energy Positrons and the WMAP Haze from Exciting Dark Matter”**, I. Cholis, L. Goodenough and N. Weiner, Phys. Rev. D **79**, 123505 (2009) [arXiv:0802.2922 [astro-ph]]

30. **“Nonstandard Higgs Boson Decays”**, S. Chang, R. Dermisek, J. F. Gunion and N. Weiner, Ann. Rev. Nucl. Part. Sci. **58**, 75 (2008) [arXiv:0801.4554 [hep-ph]]

31. **“Mixed Sneutrinos, Dark Matter and the LHC”**, Z. Thomas, D. Tucker-Smith and N. Weiner, Phys. Rev. D **77**, 115015 (2008) [arXiv:0712.4146 [hep-ph]]

32. **“Flavor in supersymmetry with an extended R-symmetry”**, G. D. Kribs, E. Poppitz and N. Weiner, Phys. Rev. D **78**, 055010 (2008) [arXiv:0712.2039 [hep-ph]]

33. **“Nonstandard Higgs Decays with Visible and Missing Energy”**, S. Chang and N. Weiner, JHEP **0805**, 074 (2008) [arXiv:0710.4591 [hep-ph]]

34. **“Sensitivity and Insensitivity of Galaxy Cluster Surveys to New Physics”**, J. Erlich, B. Glover and N. Weiner, JCAP **0803**, 006 (2008) [arXiv:0709.3442 [hep-ph]]

35. **“Exciting Dark Matter and the INTEGRAL/SPI 511 keV signal”**, D. P. Finkbeiner and N. Weiner, Phys. Rev. D **76**, 083519 (2007) [arXiv:astro-ph/0702587]