Research Interests and Experience

My research interests are focused on the fields of particle cosmology, i.e. the interplay of particle physics, cosmology, and astroparticle physics. In particular I am interested in phenomenology of particle dark matter models in theories beyond the Standard Model.

I have been working on the phenomenology of decaying dark matter models in the context of indirect dark matter searches with a focus on gravitino dark matter models with R-parity violation. A main aspect of this work has been the study of dark matter decay signals in gamma rays, antiprotons, positrons, neutrinos, and antideuterons that could be observed in earthbound and satellite cosmic-ray experiments.

Diplom Research

My research work started in late 2007 with the preparation of the diploma thesis at the DESY theory group under the supervision of Laura Covi. In collaboration with Laura Covi, Alejandro Ibarra and David Tran I worked on the phenomenology of a model of gravitino dark matter with broken R-parity [1, 2]. A model of this type can reconcile thermally produced gravitino dark matter with the generation of the baryon asymmetry via thermal leptogenesis in the early universe. This scenario was particularly appealing at that time since it could explain the rise in the cosmic-ray positron fraction as observed by the PAMELA satellite although the scenario was invented earlier and for different reasons. However, as a single type of observation cannot be unambiguously interpreted as a signal of particle dark matter, it was very important to study complementary cosmic-ray channels in a multi-messenger approach.

In this setup I calculated the decay widths of the R-parity violating two-body decay channels of the gravitino lightest supersymmetric particle and determined the resulting neutrino spectra. The latter contain several lines from different two-body decay channels, which would be a smoking gun for a dark matter origin of the signal. On one hand, it turned out that the expected neutrino flux at the Earth is overwhelmed by atmospheric muon neutrinos for typical gravitino lifetimes suggested by cosmic ray positron observations. On the other hand, one could use tau neutrinos for detection since they have a much lower background. We found that in this channel the expected neutrino flux could dominate over the background and therefore detection of a dark matter signal were possible if tau neutrinos could be observed and identified reliably. In the case of no detection, strong bounds on the gravitino lifetime could be obtained.

Doctoral Research

I prepared my doctoral thesis at the DESY theory group under the supervision of Laura Covi. Motivated by the activity in dark matter phenomenology after the publication of the results of the PAMELA satellite, I started a model-independent analysis of neutrino signals from dark matter decays together with Laura Covi, Alejandro Ibarra and David Tran [3]. I determined the expected neutrino fluxes from different decay channels of scalar and fermionic dark matter particles and compared them to the observed neutrino flux at the Earth. In order to find more sophisticated limits on the dark matter mass and lifetime I investigated different event topologies in neutrino experiments: upward through-going muons, stopping muons and electromagnetic and hadronic showers. It turns out that showers are the most promising channel for the detection of neutrinos coming from dark matter decays. I also found that the IceCube neutrino experiment should be able to probe the decaying dark matter parameter range needed to explain the PAMELA and Fermi LAT data.

For my thesis I studied in more detail the model of gravitino dark matter with broken R-parity mentioned above [4, 5]. For this I reviewed the calculation of gravitino decay widths, including also three-body decays that become important for gravitino masses below the threshold for the on-shell production of W bosons. Studying the signals from gravitino decay in all possible cosmic-ray channels, i.e. gamma rays, positrons, antiprotons, antideuterons, and neutrinos, I found that they cannot explain the excesses in the PAMELA and Fermi LAT data. Using this multi-messenger approach I could set bounds on the gravitino lifetime and thereby also on the size of R-parity violation in the model. While gamma-ray line searches set the most stringent bounds for light gravitinos, limits from the diffuse gamma-ray flux and antiprotons are comparable in strength over a wide range of masses. Neutrino observations become sensitive for multi-TeV gravitino masses, while antideuteron searches could be relevant at low masses. In addition, I studied how the situation for a direct detection of gravitino dark matter improves in the case of broken R-parity. It turned out that the cross section of inelastic gravitino scattering off nuclei is much larger than the elastic scattering cross section in the case of conserved R-parity. Unfortunately it is still way too small to hope for a signal in direct detection experiments.

Current Projects

Currently, I am working on several projects connected to the phenomenology of gravitino dark matter and decaying dark matter in general. In collaboration with Timur Delahaye I am reviewing constraints from observations of charged cosmic rays and gamma rays on the parameter space of gravitino dark matter and fermionic decaying dark matter in general. We are also studying the prospects for the observation of cosmic-ray antideuterons, taking into account the constraints from other cosmic-ray channels. In the same class of models, together with Roberto A. Lineros, I am studying the radio signals produced in the interaction of the Galactic magnetic fields with the electrons and positrons produced in gravitino decays. In collaboration with Sanjib K. Agarwalla I am also studying neutrino signals from decaying dark matter models in current and future neutrino experiments. In addition, together with Germán A. Gómez-Vargas, Carlos Muñoz and Christoph Weniger I am studying how gamma-ray line searches at sub-GeV to GeV energies in the data of Fermi LAT and future gamma-ray observatories can be used to constrain the parameter space of decaying gravitino dark matter in the context of the $\mu\nu$SSM. Finally, together with Laura Covi I am working on a more thorough study of the effects of R-parity violating interactions of gravitino dark matter in the context of direct detection experiments.

Future Plans

In the near future I would like to continue working on dark matter phenomenology since I expect that in the next years there will be a lot of input from current and forthcoming cosmic-ray experiments like Fermi LAT, AMS-02 and CTA, as well as from neutrino experiments like IceCube, KM3NeT and Hyper-Kamiokande. In addition, a multitude of dark matter direct detection experiments will further investigate the parameter space of WIMP dark matter models and shed light on reported hints for light dark matter and inconsistencies between the claims of current experiments. Also, the LHC is performing very well and after the discovery of a candidate for the Higgs boson we might also hope for signals of physics beyond the Standard Model in the near future. Such prospects motivate me to extend my previous research also to these areas. Therefore, I plan to broaden my field of interest to phenomenological studies of dark matter signals at underground detectors and colliders and I would welcome to join projects in these directions. I would also welcome close collaboration with experimental groups in this research area.

Apart from dark matter I am keen to study phenomenology of physics beyond the Standard Model in general, particularly collider signals expected from supersymmetry and supergravity models. For instance scenarios with gravitino dark matter can have long-lived next-to-lightest supersymmetric particles, leading to exciting new collider signatures and the possibility to measure the Planck mass from particle physics. On the theoretical side I am interested in grand unified theories and mechanisms of supersymmetry breaking and its mediation to the visible sector.

Another intriguing field of research is the application of particle physics to processes in the early universe, for instance the generation of the baryon asymmetry in the universe, production mechanisms of particles after an inflationary phase, and big bang nucleosynthesis. The impact of new physics models on these mechanisms allows to probe physics at very high energy scales by demanding a consistent cosmological model. Thus the early universe is a fascinating place to study theories beyond the Standard Model and I would be excited to participate in new developments in this field.

Due to my work in dark matter phenomenology I also became interested in astroparticle physics and neutrino physics. Astroparticle physics plays a crucial role in indirect dark matter searches. It is important to understand astrophysical backgrounds and also the propagation of cosmic rays in the interstellar medium. But beyond that astrophysics is a unique laboratory for searches for physics beyond the Standard Model, especially at ultrahigh energies that cannot be investigated in collider experiments. With the observation of a non-zero third neutrino angle neutrino physics is entering a new era of precision measurements in the lepton sector. As the undestanding of neutrino physics is a cornerstone for studies of physics beyond the Standard Model, it would be fascinating to follow and shape the upcoming developments in this field.

Until now we still lack a thorough understanding of fundamental questions like the nature of the dark matter, the generation of the baryon asymmetry in the universe or the smallness of neutrino masses. In the long term I would like to contribute to a solution to these problems. I am looking forward to extending my research beyond the field of dark matter and would like to participate in finding a consistent understanding of physics beyond the Standard Model and its impact on the early universe and astrophysical observations today.

References

[1] M. Grefe, "Neutrino Signals from Gravitino Dark Matter with Broken R-Parity," DESY-THESIS-2008-043 [arXiv:1111.6041 [hep-ph]].

[2] L. Covi, M. Grefe, A. Ibarra and D. Tran, "Unstable Gravitino Dark Matter and Neutrino Flux," JCAP **0901** (2009) 029 [arXiv:0809.5030 [hep-ph]].

[3] L. Covi, M. Grefe, A. Ibarra and D. Tran, "Neutrino Signals from Dark Matter Decay," JCAP **1004** (2010) 017 [arXiv:0912.3521 [hep-ph]].

[4] M. Grefe, "Unstable Gravitino Dark Matter – Prospects for Indirect and Direct Detection," DESY-THESIS-2011-039 [arXiv:1111.6779 [hep-ph]].

[5] M. Grefe, "Indirect Searches for Gravitino Dark Matter," J. Phys. Conf. Ser. **375** (2012) 012035 [arXiv:1111.7117 [hep-ph]].

Last updated: 26th October 2012.