GAMBIT: a Global and Modular Beyond the Standard Model Inference Tool (Other support - FRINATEK)

Application Number: ES512029 Project Number: -1

Applicant

Project Owner

Institution / company (Norwegian name)	UNIVERSITETET I OSLO
Faculty	DET MATEMATISK-NATURVITENSKAPELIGE FAKULTET
Institute	Fysisk institutt
Department	
Address	Postboks 1048 Blindern
Postal code	0316
City	OSLO
Country	Norge
E-mail	admin@fys.uio.no
Website	http://www.fys.uio.no/
Enterprise number	971035854
eAdministration	✔ The application is attached to eAdministration

Project administrator

First name	Lars
Last name	Bernhardsen
Position/title	Head of administration
Phone	+4722856429
E-mail	lars.bernhardsen@fys.uio.no
Confirmation	✔ The application has been approved by the Project Owner

Project manager

First name	Are

GAMBIT: a Global and Modular Beyond the Standard Model Inference Tool (Other support - FRINATEK)

Application Number: ES512029 Project Number: -1

Last name	Raklev
Institution / company (Norwegian name)	
Faculty	Faculty of Mathematics and Natural Sciences
Institute	
Department	Department of Physics
Address	P.O. Box 1048 Blindern
Postal code	0316
City	Oslo
Country	Norway
Position/title	Associate professor
Academic degree	PhD
Preferred language	Bokmål
Phone	+4722855079
E-mail	ahye@fys.uio.no

Project info

Project title

Project title	GAMBIT: a Global and Modular Beyond the Standard Model Inference Tool

Primary and secondary objectives of the project

Primary and secondary objectives	The primary aim of the project is to develop a new tool for statistical inference on new models beyond the Standard Model (SM) of particle physics from the large number data sources that are now available to researchers. The project involves multiple partners across the globe in the GAMBIT collaboration, and the specific rôle of the University of Oslo researchers involved in the project will be responsibility for the interpretation of, and interface to, accelerator data, in particular coming from the Large Hadron Collider (LHC), and future astrophysics data from the Cherenkov Telescope Array (CTA). The secondary objective of the project is to use the developed tools to perform the worlds first complete scan of the MSSM-25, a 25-parameter representation of the Minimal Supersymmetric Standard Model, using all presently available constraints.

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Project summary

Project summary	Beyond the SM (BSM) physics is well motivated, e.g. from the existence of Dark Matter (DM), and is expected to show up in multiple experiments, such as accelerator searches (LHC), neutrino mass and mixing data, and direct and indirect DM search experiments. Some of these already show tantalizing hints of DM or other BSM physics. To make robust conclusions about the level of support for a BSM scenario from such varied sources, a simultaneous statistical fit of all the data, fully taking into account relevant uncertainties, assumptions and correlations is necessary. The same is true for determining the preferred regions of parameter space within a particular model. This is a highly non-trivial task, on the border of theory and experiment, astrophysics and particle physics, and requires an excellent understanding not only of the theories and experiments involved, but also an efficient use of specialized statistical techniques and computer codes. Whilst partial progress has been made, the magnitude of the task and degree of technical difficulty have left it largely unexplored for the majority of BSM theories and datasets. With the start-up of the LHC, vast amounts of new data are rapidly becoming available, quickly making even the analyses that have been done in the past year obsolete. The research in this proposal is part of a collaboration that plans to revolutionize this emerging field, by taking publicly available data from the LHC and astrophysics experiments, and vastly expanding the scope of models to which it is applied. The aim is to develop modular tools in a framework that makes it possible to explore any BSM model, with almost all of the relevant particle and astrophysical data recorded. The focus of the project in this application is the interface to, and use of collider data, in this framework. After a period of development we will apply the tools to the best motivated BSM models in order to investigate the impact of present, and any future, discoveries

Funding scheme

Supplementary info from applicant

Programme / activity	FRINATEK
Application type	Other support
Topics	
Other relevant programmes/ activities/projects	

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Discipline(s)	High-energy physics, particle physics, astroparticle physics.
If applying for additional funding, specify project number	
Have any related applications been submitted to the Research Council and/or any other public funding scheme	No
If yes, please provide further information	

Progress plan

Project period

From date	20140701
To date	20180630

Main activities and milestones in the project period (year and quarter)

Milestones throughout the project	From		To	
Develop tool infrastructure for colliders	2014	3	2015	2
Start of postdoctoral researcher	2014	3	2014	3
Implement published LHC 8 TeV analyses	2015	1	2015	3
Extend infrastructure beyond SUSY models	2015	3	2018	2
Start of PhD-student	2015	3	2015	3
Perform first MSSM-25 scan	2015	4	2015	4
Continue to implement LHC 13 TeV analysis	2016	1	2018	2
First scan of a non-SUSY model	2016	3	2016	3
Investigate ILC reach for BSM models	2016	4	2017	4
PhD-thesis published	2018	2	2018	2

Dissemination of project results

Dissemination plan

This project concerns basic research. The plan for scientific dissemination of our results follows the standard scheme in the field: Results will be presented at major international meetings and conferences, after having been presented internally at collaboration meetings.

Results will be published in leading peer-reviewed journals, favouring scientific journals with open access policy, while the use of electronic archives (e.g. http://arxiv.org) will guarantee that open-access versions of our articles are always available.

All scientific presentations and material produced as a part of the project will be publicly available from the web. The resulting PhD-thesis will be accessible on-line from the University of Oslo.

All computer programmes developed as part of this project will be open source, owned by the authors and freely available for non-commercial use. This includes, but is not limited to, new statistical methods, code to calculate BSM model properties, Monte Carlo simulation code for experiments and the binding framework.

We will use the strong experimental contingent of our collaboration to feed the results of scans back to the leading particle and astrophysics experiments, directly influencing the course of future research.

We plan to hold open lectures for the general public and at local high schools on the search for BSM physics as a part of our public outreach strategy. Through this we aim to kindle interest for (astro)particle physics and cosmology in the public, and in particular among high school students, recognising that our recruitment to science starts there.

Budget

Cost plan (in NOK 1000)

	2014	2015	2016	2017	2018	2019	2020	2021	Sum
Payroll and indirect expenses	662	1778	2257	1826	683				7206
Procurement of R&D services									0
Equipment									0
Other operating expenses	190	405	280	260	45				1180

	2014	2015	2016	2017	2018	2019	2020	2021	Sum
Totals	852	2183	2537	2086	728				8386

Specification	Payroll and indirect expenses includes one postdoctoral and one doctoral fellowship as specified below (RCN funding), as well as a 40% FTE contribution from the project manager (own funding). Other operating expenses (RCN funding) are as follows: 150 kNOK for a workshop planned to be held in Oslo in 2015 in order to coordinate the international collaboration part of the project, 40 kNOK per year in travel expenses for the project manager, and 150 kNOK per year for the large scale computing resources needed in the project due to its heavy dependence on Monte Carlo simulation.

Cost code (in NOK 1000)

	2014	2015	2016	2017	2018	2019	2020	2021	Sum
Trade and industry									0
Independent research institute									0
Universities and University Colleges	852	2183	2537	2086	728				8386
Other sectors									0
Abroad									0
Totals	852	2183	2537	2086	728				8386

Funding plan (in NOK 1000)

	2014	2015	2016	2017	2018	2019	2020	2021	Sum
Own financing	214	392	349	351	177				1483

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	2014	2015	2016	2017	2018	2019	2020	2021	Sum
International funding									0
Other public funding									0
Other private funding									0
From Research Council	638	1791	2188	1735	551				6903
Totals	852	2183	2537	2086	728				8386

Specification

Fellowship

Type of fellowship	Post-doctoral fellowships
From date (yyyymmdd)	20140701
To date (yyyymmdd)	20170630

Type of fellowship	Doctoral fellowship
From date (yyyymmdd)	20150701
To date (yyyymmdd)	20180630

Partners

Partners under obligation to provide professional or financial resources for the implementation of the project

Attachments

Project description

Filename	gambit.pdf
Reference	ES512029_001_1_Prosjektbeskrivelse_20130528

Other items

Filename	CV.pdf
Reference	ES512029_010_1_Annet_20130520

Filename	Allocationsoughtfromtheresearchcouncil.pdf
Reference	ES512029_010_2_Annet_20130523

GAMBIT: a Global and Modular Beyond the Standard Model Inference Tool

Are Raklev

May 28, 2013

1 Relevance relative to the call for proposals

The call for proposals in the FRIPRO announcement seeks broad-based, independent basic research, with an emphasis on high scientific quality, the development of basic theory and methods, as well as scientific renewal within a discipline.

The research project described below is basic research in the field of particle and astroparticle physics, aimed at making a crucial contribution to the search for physics Beyond the Standard Model (BSM), using the latest data from leading particle and astrophysics experiments. The project is part of an international collaborative effort to develop a new tool for statistical inference, the `GAMBIT` software package (for Global And Modular Bsm Inference Tool), which will give users a novel way to look at the available large data-sets with arbitrary new physics models and statistical methods. In this way the project has the potential to dramatically enhance work at the interface of particle theory and experiment, bringing in new methods to tackle the old problem of BSM searches and parameter determination in models.

2 Aspects relating to the research project

2.1 Background and status of knowledge

We are living in the golden age of particle physics. The Standard Model (SM) explains, in the language of gauge field theory, what the basic building blocks of the universe are, and how they interact. Its predictions have been confirmed experimentally with spectacular accuracy, in part at the level of one in ten million. The recent discovery of a Higgs-like boson [1, 2] in the proton–proton collisions at the Large Hadron Collider (LHC), gives us for the first time an experimental probe of the origin of mass, and ranks as one of the

greatest scientific achievements in history. This tremendous progress in our measurements of the smallest scales of Nature is matched by outstanding leaps forward in our understanding of the universe as a whole. Astrophysicists have combined observations of galaxy rotation curves, gravitational lensing measurements and precision measurements of the cosmic microwave background to discover that 80% of the matter in the universe is composed of a strange form of Dark Matter, for reviews see [3, 4]. Its nature is still unknown: astrophysics inform us only that the DM particle should not have electromagnetic interactions, it should be non-baryonic, dissipation-less and non-relativistic at the time it decoupled from other matter in the early universe.

However, Dark Matter and the Higgs boson both severely challenge the SM. In the former case, the theory contains no particles that fit the DM properties unless we extend it. In the latter case, the size of the Higgs mass is a great many orders of magnitude below that expected by the structure of the theory, requiring an enormous and highly uncomfortable fine tuning of the underlying parameters in order to reproduce the observed value of 125 GeV, the so-called *hierarchy problem*. It is widely assumed, therefore, that the SM is a low energy effective theory, and at higher energy scales one will observe new particle content and new physics capable of providing a natural explanation for the low energy behaviour. Many candidates exist in the literature, *e.g.* supersymmetry and extra-dimensional theories, that can solve the Dark Matter and hierarchy problems with new physics at the TeV scale, that we are just now starting to probe in experiments.

> *The current biggest challenge in particle and astroparticle physics is to determine which Beyond the Standard Model theory solves these problems. The central theme of this project is to help address this challenge.*

2.2 Approaches, hypotheses and choice of method

Beyond the SM physics is expected to show up in multiple experiments, such as accelerator searches, low-energy precision measurements, neutrino mass and mixing data, and direct and indirect DM search experiments. Some of these already show tantalising hints of DM or other BSM physics, see *e.g.* [5, 6]. To make robust conclusions about the level of support for a particular BSM scenario from such varied sources, a simultaneous statistical fit of all the data, fully taking into account relevant uncertainties, assumptions and correlations is necessary. The same is true for determining the preferred regions of parameter space within a particular model. This is a highly non-trivial task, on

the border of theory and experiment, astrophysics and particle physics, and requires an excellent understanding of the theories and experiments involved, and an efficient use of specialised statistical techniques and computer codes in large scale Monte Carlo (MC) simulations.

Whilst partial progress has been made [7], the magnitude of the task and degree of technical difficulty has left it largely unexplored for the majority of the many BSM theories that exists and the large number of data-sets that are now available. With the start-up of the LHC, vast amounts of new data are rapidly becoming available, quickly making even the analyses that have been done in the past year obsolete.

The research in this proposal is part of a collaboration, the GAMBIT Collaboration, that plans to revolutionise this emerging field, by taking publicly available data from the LHC, and other particle and astrophysics experiments, and greatly expanding the scope of models to which it is applied. The aim is to develop modular tools in the `GAMBIT` software framework that makes it possible to explore any BSM model, with almost all of the relevant particle and astrophysical data recorded. The fundamental method used is the calculation of a likelihood based on the observables in a model, compared to published data. The likelihood evaluation is done by statistical sampling methods, where the user will be free to choose from a wide range suiting different purposes. The resulting likelihood, as a function of model parameters, can then be interpreted in frequentist and/or Bayesian frameworks as desired.

The focus of the project in the current application is the interface to, and use of collider data, including the proposed International Linear Collider (ILC), and the use of future astrophysics data from the Cherenkov Telescope Array (CTA) in the `GAMBIT` framework. Calculating a model likelihood, based on *e.g.* LHC observables, can be done using standard tools in a two step process. First, one uses a MC event generator to simulate the physics of new particle production in proton–proton collisions, before passing the results through the simulation of an LHC detector. A rough calculation shows that this currently takes about an hour per likelihood point for a typical LHC analysis, which is far too slow to obtain convergent fits in large parameter spaces, even with the most sophisticated statistical techniques. We aim to reduce this calculation time to $\mathcal{O}(10\,\mathrm{s})$ by parallelising the simulation code using high performance computing, and/or using machine learning algorithms to interpolate grids of previously simulated data. These novel approaches will provide the most advanced available solutions for calculating LHC likelihoods, and are the only known methods that will allow us to effectively explore parameter spaces of high dimension.

After a period of development we will apply the tools to the best motivated BSM models in order to investigate the impact of present, and any future, discoveries.

To achieve the overall aims of the project, we will solve the following specific research tasks:

1. With the GAMBIT Collaboration, **contribute to the development of a new tool for statistical inference on BSM theories** from the large number data sources that are now available.

2. Develop modules for the **efficient calculation of likelihoods for LHC, ILC and CTA data** within the `GAMBIT` framework.

3. Perform the **worlds first convergent scan of the MSSM-25**, the Minimal Supersymmetric Standard Model with 25 free parameters, using all presently available constraints.[1]

2.3 The project plan

The project runs over four years and will be a team effort between two temporary positions in Oslo, one postdoctoral (three years) and one PhD-fellow (three years), and the project manager. The postdoc and PhD-positions will be advertised internationally, and start in 2014 and 2015, respectively. The postdoc will focus on the development of the Supersymmetry framework in `GAMBIT` in relation to BSM searches at colliders and its exploitation in constraining popular Supersymmetry models on the basis of LHC data. The PhD-student will perform similar work on non-Supersymmetric models, and on prepare for future data from an ILC and the Cherenkov Telescope Array.

Because of the connection to the GAMBIT Collaboration as a whole, there will be considerable involvement with external collaborators. This takes the form of monthly phone-meetings and regular visits, both to Oslo and at the other institutions involved (see below), as well as a yearly workshop. Some comment must be made on the risks of collaboration: while the whole `GAMBIT` framework requires the work of many people, experts in their own field, the design is highly modular. So modular in fact, that individual modules are designed to be usable on their own. This means that even in a worst-case scenario the methods developed in this project can be used stand-alone, or with other finished parts of the `GAMBIT` framework, to give novel physics results.

[1] This is five times as many parameters as the simple models typically considered in the literature, and has the potential to tell us directly what distinct supersymmetric theories, if any, are still capable of providing solutions to the Dark Matter and hierarchy problems.

Below we describe the details of the project plan in yearly intervals (not corresponding to calendar years, but from the start of the project):

1st year

Postdoc: In collaboration with the project manager, the postdoc should start by following-up the on-going development of necessary infrastructure in the `GAMBIT` framework for handling the results of collider data in searches for Supersymmetry. This involves building modules that interface Monte Carlo programs for the simulation of supersymmetric particle production and the resulting detector response with the other parts of the framework, also implementing a structure for the coding of specific analysis. Overlapping with this, the postdoc should start the implementation of analysis of published 8 TeV LHC data and begin large scale Monte Carlo testing of the programme structure on simplified models, in order to eliminate bugs and increase the efficiency of scans, which is vital to the success of tasks in the next year.

2nd year

Postdoc: Continue implementation of 8 TeV analysis. Take part in the first `GAMBIT` full scan of the MSSM-25 parameter space with the publication of the first major `GAMBIT` physics paper and the public code. This will require access to large scale computing resources as described in the budget section. Start to implement analysis from the high-energy LHC at $\sim$ 13 TeV as they are published. Ongoing transfer of knowledge to PhD-student.
PhD-student: Begin by learning how LHC analysis from the first phase 2010–2012 sets bounds on new physics models. Extend the `GAMBIT` infrastructure for collision data to BSM theories beyond Supersymmetry in collaboration with the project manager and the postdoc.

3rd year

Postdoc: Continue the implementation of 13 TeV analysis from the LHC. Together with PhD-student, begin the implementation of possible future analysis from an International Linear Collider and astrophysics results from the Cherenkov Telescope Array.
PhD-student: Participate in the first `GAMBIT` large scale scan of a non-Supersymmetry BSM theory. The particular model is still to be decided upon, but will probably be an extra-dimensional model motivated by the current status of searches and precision measurements. Continue the development of infrastructure for new BSM theories.

4th year
PhD-student: Continue the development of infrastructure for new BSM theories. Take over the implementation of 13 TeV analysis from the postdoc that has now left, and study the reach of the ILC and CTA in the remaining parameter space of models that have already been investigated on the basis of LHC and other current results. Publish PhD-thesis at the end of the year.

2.3.1 Project management

This particular application is within the Young Research Talents category, targeted towards researchers in the early stage of their careers, who have demonstrated an ability to conduct high quality research. The project manager has since his PhD in 2007 published a significant amount of independent research in leading journals in the field, research which has been highly cited. He has a large international scientific network of past and current collaborators, and has already acquired considerable experience in research management, *e.g.* as a member of the steering committee for the Norwegian High-Energy Particle Physics (HEPP) project. He also has relevant experience supervising students, having successfully supervised three masters-level students, of which two have gone on to do PhDs, and is currently supervising two PhD-students in their third year.

For more details on the project manager, please see the attached CV.

2.3.2 Organization and cooperation

With regards to the PhD-fellowship sought in the project: the Department of Physics in Oslo has a long and very strong record in supervising PhD-candidates. It has an excellent teaching environment and offers a broad range of high-level courses that are relevant to the project, such as a specialised master and PhD-level course in Supersymmetry. Candidate progress is followed closely with yearly reports to an independent PhD-committee. Each candidate is assigned a secondary supervisor, both as a back-up and as a channel for communication in case of difficulties.

One of the long term aims of this proposal is to create more fertile ground in Norway for research on the border between particle and astrophysics. The project will seek to strengthen already existing links between the theoretical DM research in Oslo and other Norwegian groups. Most relevant are the experimental particle physics groups in Oslo and Bergen, involved in the ATLAS experiment at the LHC, the theory work on cosmic rays at NTNU in Trondheim, and the Institute of Theoretical Astrophysics in Oslo. Expertise from

Member	Institution
Professor Csaba Balazs	Monash University, Australia
Dr Torsten Bringmann	DESY, Germany (UiO from fall 2013)
Dr Andy Buckley	University of Edinburgh, UK
Professor Jan Conrad	Stockholm University, Sweden
Professor Joakim Edsjö	Stockholm University, Sweden
Dr Abram Krislock	Stockholm University, Sweden
Dr Nazila Mahmoudi	CERN Theory Division, Switzerland
Dr Antje Putze	University of Aachen, Germany
Assoc. Prof. Are Raklev	University of Oslo (UiO), Norway
Dr Aldo Saavedra	University of Sydney, Australia
Dr Christopher Savage	University of Utah, USA
Dr Pat Scott	McGill University, Canada
Dr Christoph Weniger	University of Amsterdam, Netherlands
Dr Martin White	University of Melbourne, Australia

Table 1: Current members of the GAMBIT Collaboration.

all these sources will be valuable in different sub-goal of the project, *e.g.* in the application of experimental bounds from Supersymmetry searches at the LHC, the intimate knowledge of analysis details that exists in the experimental groups may be vital. We will enhance these existing links through common seminars and common supervision of students.

The project will also benefit from a forthcoming strengthening of astroparticle research at the Department of Physics in Oslo: Dr Torsten Bringmann, also a member of the GAMBIT Collaboration, will take up a position as Associate Professor in cosmology/theoretical astroparticle physics in October 2013. In January 2015, Dr Heidi Sandaker, a member of the CTA Collaboration, will move to Oslo as Associate Professor in experimental particle physics.

The project is a part of the GAMBIT Collaboration, an international collaboration of theorists and experimentalists in the fields of particle and astrophysics. The members of `GAMBIT` at the time of application (omitting PhD-students), along with their home institutions, can be found in Table 1. This demonstrates the extent of the international cooperation that the project is involved in. The use of the expertise of these collaborators will be an important resource for the tasks that the project will solve within `GAMBIT`.

The GAMBIT Collaboration is formalised through a policy document that all participants have agreed to. The collaboration has monthly full collaboration phone-meetings, and more frequent working-group meetings. Phone-

meetings are necessary because of the great physical distances involved. Major decisions are made at a yearly in-person collaboration meeting and workshop. We seek money to organize one such meeting (see below).

2.4 Budget

The main expenditure in the budget is the funding for one PhD-fellowship and one postdoc, both for 3 years ($\sim$ 6 MNOK in total), with the positions staggered over 4 years to ensure knowledge transfer, and to make bridges to other sources of funding. The second biggest item is money for large scale computing resources, $\sim$ 150 kNOK per year. High performance computing is vital for efficient Monte Carlo simulation in the parameter space scans that will give the physics results of the project, and also in testing the software developed (see Sec. 2.3).

In addition, we ask for funding to organize a workshop in Oslo in the summer of 2015 for the whole GAMBIT Collaboration, the cost of which has been estimated at 150 kNOK. The main purpose of the workshop is to coordinate collaboration between the participating groups. For the workshop we also intend to invite 2–3 outside speakers, and aim to give talks to interested local physicists, both on the `GAMBIT` tools, and on the physics involved. This will be an excellent opportunity to promote particle and astroparticle physics in Norway. We also ask for some limited travel support (40 kNOK per year). Please see the grant application form for further details.

3 Key perspectives and compliance with strategic documents

3.1 Compliance with strategic documents

The recent international evaluation report on Norwegian basic physics research commissioned by the Research Council of Norway (RCN) [8], see *e.g.* Secs. 3.1.1, 3.1.8 and 3.1.9 of that report, highly recommends coordinated national activities and collaboration on the border between particle and astrophysics, towards which this project is a stepping-stone. The research topics addressed by the project are also well aligned with local strategy documents for the Department of Physics in Oslo and its Theory group, where a significant contribution to the search for Dark Matter is a key goal.

If funded, the proposal will not only bolster current research, but also allow for important positioning and profiling internationally, in preparation

for applications to EU funded projects and for a Centre-of-Excellence from the RCN.

3.2 Relevance and benefit to society

Funding fundamental research has often shown itself to be more effective in the long term in generating an innovative industry and society than solely channelling research money to applied research. The best known spin-off of particle physics research is the world-wide-web technology, created originally at CERN to share information between particle physicists from all over the world. Similarly, automated analysis techniques developed to analyze the enormous amount of images and data produced by modern astronomical telescopes have found application in imaging techniques used in medicine.

While it is not easy to predict what concrete benefit society will have from the research in this project, it is very likely that new techniques developed in a cutting-edge area of contemporary physics research will have a positive long term impact on society, *e.g.* the project's development of modular statistical tools for use on large data-sets can readily be applied to other data-sets, whether in medicine, finance or elsewhere.

3.3 Environmental impact

The project has no particular environmental aspects.

3.4 Ethical perspectives

The project has no particular ethical aspects. We will comply with the guidelines of the respective scientific communities when it comes to authorship of scientific work and citations, and the use of open source software.

3.5 Gender issues

In Norway, high-energy physics is a field with a rather low fraction of female researchers. This trend follows traditional job segregation and low percentage of women in exact sciences observed in Nordic countries. We will seek to improve on this situation by actively seeking good female candidates for the two fellowships in the project through our research network, and recruiting internationally. The University of Oslo aims to become a more family-friendly work place, *e.g.* by encouraging equal maternity/paternity leave and providing more support facilities for parents.

4 Dissemination of results

4.1 Dissemination plan

Our strategy for research results and popular science dissemination activities is presented in detail on the grant application form.

4.2 Communication with users

This project has a potentially very large user base in high-energy physics model building and phenomenology, and among the relevant experiments, through the tools that are to be developed. The information channels we will use are the following: hosting of the tools in a development environment for high-energy physics software projects, `HepForge` [9], the publication of a user manual in relevant computing journals, mailing lists, and a wiki based information source for the tools together with a bug tracking system.

References

[1] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716** (2012) 1 [arXiv:1207.7214 [hep-ex]].

[2] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716** (2012) 30 [arXiv:1207.7235 [hep-ex]].

[3] G. Bertone, D. Hooper and J. Silk, Phys. Rept. **405**, 279 (2005) [hep-ph/0404175].

[4] L. Bergstrom, New J. Phys. **11**, 105006 (2009) [arXiv:0903.4849 [hep-ph].

[5] T. Bringmann, X. Huang, A. Ibarra, S. Vogl and C. Weniger, JCAP **1207** (2012) 054 [arXiv:1203.1312 [hep-ph]].

[6] M. Aguilar *et al.* [AMS Collaboration], Phys. Rev. Lett. **110** (2013) 14, 141102.

[7] S. S. AbdusSalam, B. C. Allanach, F. Quevedo, F. Feroz and M. Hobson, Phys. Rev. D **81** (2010) 095012 [arXiv:0904.2548 [hep-ph]].

[8] B. Gustafsson *et al.*, "Basic Physics Research in Norway – An Evaluation," Oslo: RCN (2010).

[9] `http://www.hepforge.org/about`

Curriculum Vitae

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Current Position

Associate professor in theoretical high energy physics at the Department of Physics, University of Oslo (UiO), Norway (October 2010 –).

Previous positions

- **Postdoctoral position** at the Oskar Klein Centre for Cosmo Particle Physics (OKC), Stockholm University, Sweden (October 2009 – September 2010).
- **Research Associate** at the Department of Applied Mathematics and Theoretical Physics (DAMTP), University of Cambridge, UK (October 2007 – September 2009).
- **Postdoctoral position**, at the Department of Physics and Technology, University of Bergen, Norway (June 2007 – September 2007).
- **Mathematics lecturer**, at Sør-Trøndelag University College, Department of Food Technology, Trondheim, Norway (August 2003 – December 2003).
- **Mathematics lecturer**, at Sør-Trøndelag University College, Faculty of Technology, Trondheim, Norway (January 2001 – June 2001).

Education

- **Ph.D. in Particle Physics**, June 2007, University of Bergen, Norway.
  Ph.D. supervisors: Per Osland (theory), Anna Lipniacka (ATLAS experiment).
  Thesis title: *Supersymmetric decay chains at the LHC.*
- **M.Sc. in Particle Physics**, July 2002,
  Norwegian University of Science and Technology (NTNU), Trondheim, Norway.
  Thesis title: *Coupling constants in the Minimal Supersymmetric Standard Model.*
- **B.Sc. in Physics**, July 2000, NTNU, Trondheim, Norway.

Awards, grants and scholarships

- **Grant for NORDITA programme** on *Beyond the LHC* in July 2013 (500 kSEK).
- **UiO support grant** (PES) for ERC application 2012 (50 kNOK).
- **UiO support grant** (PES) for ERC application 2011 (32 kNOK).
- **Andreij Sakharov Diploma,** awarded at the International School of Subnuclear Physics, Erice, September 2007 (Directors A. Zichichi and G. 't Hooft).
- **Marie Curie Fellowship for Early Stage Training** (February 2006 – January 2007). One year fellowship hosted by CERN.
- **Research Council of Norway Overseas Research Grant** (January 2005 – July 2005). Grant for a six month stay at CERN.
- **Research Council of Norway Doctoral Fellowship** (January 2004 – October 2007). Personal grant for a three-year full-time position for doing research leading to a Ph.D.

Teaching and supervision

- **Completed** course on university pedagogics at UiO, 100 hours total (Spring term 2013).
- **Lecturer** in FYS5120 Supersymmetry at UiO (Fall term 2011).
- **Lecturer** in FYS2140 Quantum Physics at UiO (Spring term 2011, 2012 & 2013).

- ◇ **Supervisor** for two PhD students at UiO (September 2011 –)
- ◇ **Supervisor** for two Masters Degree students at UiO (October 2010 – June 2012)
- ◇ **Tutor** at BUSSTEPP 2008 and 2009.
- ◇ **Project supervisor** for Part III Project student, Cambridge (October 2008 – May 2009).
- ◇ **Discussion leader** at the 2009 Hadron Collider Physics Summer School (8–17 June 2009).
- ◇ **Supervisor** for Part III Particle Physics, Cambridge (Michaelmas Term 2008).

OTHER PROFESSIONAL ACTIVITIES

- ◇ **Member** of the programme board of the Research Council of Norway's International Scholarship Section since Janaury 2013.
- ◇ **Member** of the adjudication committee for the PhD thesis of Yngve Levinsen, UiO, September 2012.
- ◇ **Member** of the scientific evaluation committee for applicants to the position of Associtate Professor in Theoretical Physics at UiO, January–July 2012.
- ◇ **Member** of the Steering Committee for the Norwegian High Energy Particle Physics project since March 2012.
- ◇ **Deputy leader** of the Norwegian Physical Society's group for Subatomic Physics and Astrophysics since June 2011.
- ◇ **Member** of the NORDITA Research Committee for Subatomic Physics since October 2010.
- ◇ **Co-organizer** of the NORDITA Beyond the LHC programme (1–27 July, 2013).
- ◇ **Co-chair** of the organizing committee for the OKC PROSPECTS Workshop (15–17 September, 2010).
- ◇ **Referee** in Journal of Physics G, Journal of High Energy Physics and Physical Review D.
- ◇ **Organizer** of the HEPP Colloquia at the Department of Physics, UiO (April 2012 –)
- ◇ **Organizer** of the Cavendish-DAMTP HEP phenomenology seminar series (October 2007 – September 2009)

RESEARCH INTERESTS

The search for Dark Matter in space and at the LHC. The phenomenology of supersymmetry and other New Physics at the LHC. In particular the LHC's potential for constraining many-dimensional parameter spaces of New Physics models and for discovering non-minimal models. Also interested in cosmological constraints on supersymmetric models, in particular with gravitino dark matter and R-parity violation.

CURRENT RESEARCH PROJECTS

- ◇ Methods for measuring massive metastable charged particles at the LHC, focusing on scenarios with gravitino dark matter.
- ◇ Jet characteristics in LHC events as a tool for finding and measuring the masses of new particles with hadronic decays.
- ◇ Calculating and utilising analytical expressions for the distributions of invariants formed by the detectable SM decay products in New Physics cascade decays.
- ◇ Scenarios with light scalar tops motivated by electroweak baryogenesis and dark matter.
- ◇ The cosmology, astrophysics and LHC phenomenology of gravitino dark matter in R-parity violating supersymmetric models.
- ◇ The exploration of many-dimensional parameter spaces in New Physics models using statistical inference from large data sets.

LIST OF PUBLICATIONS

- ◇ **See separate list of publications.**

SELECTED OUTREACH ACTIVITIES

- ◇ **Topp ti mysterier i fysikk,** (Top ten physics mysteries)
  Popular science seminar for the Biørnegildet student festival, Oslo, 15 February 2013.

- ◇ **Mørk materie — hvordan finne den?** (Dark Matter — how to find it?)
  Invited talk at Realistforeningen (the Natural Sciences Student Society in Oslo), 21 September 2012.
- ◇ **Hvorfor Higgs?** (Why Higgs?)
  Invited talk at Samfundet (the Student's Society in Trondheim), 1 September 2012.
- ◇ **På leting etter Higgs,** (Searching for the Higgs)
  Seminar for high school students at Trondheim Cathedral School, Trondheim, 31 August 2012.
- ◇ **Jakten på Higgs,** (The Higgs hunt)
  Invited talk at the Norwegian Physics Students Union's yearly meeting, 10 March 2012.
- ◇ **Universet som forsvant,** (The Universe that disappeared)
  Invited talk at UiO Open Day for Norwegian High School students, 8 March and 15 November 2012.
  Invited talk to high school teachers at UiO Pedagogics Day, 1 November 2012.
  Invited talk at Norwegian Mini-Winter School, CERN, 7 November 2012.
- ◇ **Higgsjegerne,** (Higgs hunters)
  One of three contributors to Norwegian popular science blogg on Higgs searches since July 2011.
- ◇ **Masseproblemer,** (Mass problems)
  Talk at LHC Physics Day, Department of Physics, UiO, 21 October 2010.

MEDIA

- ◇ **Panel member** on popular science talk show *Abels Tårn* on national radio broadcaster (NRK), 20 May 2011 & 14 December 2012.
- ◇ **Interview** in Aftenposten (national newspaper), *Jakten på det usynlige* (The hunt for the invisible), 7 December 2012.
- ◇ **Interview** in Apollon (UiO research magazine) *Revolusjonerende teori om mørk materie* (Revolutionary theory of Dark Matter), September 2012.
- ◇ **Opinion piece** in Adressavisen (national newspaper) *NTNU svikter CERN* (NTNU lets CERN down), 20 September 2012.
- ◇ **Interview** on Radio Revolt (student radio) popular science program *Uillustrert vitenskap*, on the Higgs hunt, 15 September 2012.
- ◇ **Op-ed** in Aftenposten (national newspaper) *Oppdagelsen av en ny partikkel* (The discovery of a new particle), 7 July 2012.
- ◇ **Interview** in Dagbladet (national newspaper) *Bli kjent med Higgs* (Get to know Higgs), 6 July 2012.
- ◇ **Interview** by NTB (Norwegian news agency) *Den største partikkeloppdagelsen siden elektronet* (The greatest particle discovery since the electron), 4 July 2012.
- ◇ **Live interview** on TV2 (national television) news program on the results of the Higgs hunt, 4 July 2012.
- ◇ **Interview** in Dagbladet (national newspaper), *Må vente før Einstein teori avvises* (Must wait before Einstein's theory is disproven), 24 February 2012.
- ◇ **Interview** on Radio Nova (student radio) popular science show *Vitenselskapet* on the Higgs hunt, 24 January 2012.
- ◇ **Interview** on NRK (national radio) in popular science program *Ekko* on *CP-violation in D-meson decays*, 5 December 2011.
- ◇ **Live interview** on Radio Nova (student radio) breakfast show on *Faster than light neutrinos and Special Relativity*, 9 October 2011.

RECENT INVITED TALKS

- ◇ **Gravitino Dark Matter – on Earth and in the Sky,**
  Theory talk at the ATLAS Astro Forum, CERN, 6 November 2012.
- ◇ **Gravitino – the black sheep sparticle,**
  Talk at the Institute of Theoretical Astrophysics, Oslo, 19 October 2012.
- ◇ **Dark Matter Searches, on Earth and in the Sky,**
  Talk for NORDITA Board Meeting, University of Oslo, 24 May 2012.
- ◇ **Exploring SUSY models with RGE codes,**
  HEP Colloquium Series, University of Oslo, 11 May 2012.
- ◇ **Low energy supersymmetry - the MSSM,**
  Four lectures at the NORDITA Winter School 2012 on Theoretical Particle Physics, NORDITA, 9–20 January 2012.
- ◇ **Boosting SUSY,**
  Boost 2010 Workshop, Oxford University, 22–25 June 2010.
- ◇ **Jet substructure and SUSY,**
  Virtual Theory Institute Seminar, University of Heidelberg, 14 June 2010.
- ◇ **Determining the dark matter particle's mass at the LHC,**
  Galileo Galilei Institue for Theoretical Physics, 10 June 2010.
- ◇ **Gravitinos — here, there and everywhere,**
  Cavendish HEP Seminar, University of Cambridge, 9th March 2010.
- ◇ **Seeing Dark Matter vs. seeing it's Dark Matter,**
  Oskar Klein Centre seminar, Stockholm University, 8th December 2009.
- ◇ **Jet-algorithms and New Physics at the LHC,**
  High Energy Physics Colloquium, University of Oslo, 15th May 2009.
- ◇ **Decaying Gravitino Dark Matter,**
  High Energy Physics seminar, University College London, 27th March 2009.
  Particle physics seminar, University of Oxford, 5th March 2009.
  IPPP seminar, University of Durham, 29 January 2009.
- ◇ **Using jet properties in sparticle mass reconstruction,**
  Focus Week on Determination of Masses and Spins of New Particles,
  IPMU, Tokyo, 16–20 March 2009.
- ◇ **On the eve of the LHC,**
  Physics seminar, University College Cork, 9th March 2009.
  Physics seminar, Norwegian University of Science and Technology, 3 October 2008.

Publication list

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JOURNAL PUBLICATIONS

◇ **Boosted objects: A Probe of beyond the Standard Model physics.**
A. Abdesselam *et al.*,
Eur. Phys. J. C **71** (2011) 1661 [arXiv:1012.5412 [hep-ph]].

◇ **Photon, Neutrino and Charged Particle Spectra from R-violating Gravitino Decays.**
N.-E. Bomark, S. Lola, P. Osland and A. R. Raklev,
Phys. Lett. B **686** (2010) 152 [arXiv:0911.3376 [hep-ph]].

◇ **Neutralino Reconstruction at the LHC from Decay-frame Kinematics.**
Z. Kang, N. Kersting, S. Kraml, A. R. Raklev, M. J. White,
Eur. Phys. J. **C70** (2010) 271-283 [arXiv:0908.1550 [hep-ph]].

◇ **Discovering baryon-number violating neutralino decays at the LHC.**
J. M. Butterworth, J. R. Ellis, A. R. Raklev and G. P. Salam,
Phys. Rev. Lett. **103** (2009) 241803 [arXiv:0906.0728 [hep-ph]].

◇ **Massive Metastable Charged (S)Particles at the LHC.**
A. R. Raklev,
Mod. Phys. Lett. A **24** (2009) 1955 [arXiv:0908.0315 [hep-ph]].

◇ **Gravitino Dark Matter and the Flavour Structure of R-violating Operators.**
N.-E. Bomark, S. Lola, P. Osland and A.R. Raklev,
Phys. Lett. B **677** (2009) 62 [arXiv:0811.2969 [hep-ph]].

◇ **NSSM in disguise: discovering singlino dark matter with soft leptons at the LHC.**
S. Kraml, A.R. Raklev and M.J. White,
Phys. Lett. B **672** (2009) 361 [arXiv:0811.0011 [hep-ph]].

◇ **Radiative gravitino decays from R-parity violation.**
S. Lola, P. Osland and A.R. Raklev,
Phys. Lett. B **656** (2007) 83 [arXiv:0707.2510 [hep-ph]].

◇ **Reconstructing sparticle masses using hadronic decays.**
J.M. Butterworth, J.R. Ellis and A.R. Raklev,
JHEP **0705** (2007) 033 [arXiv:hep-ph/0702150].

◇ **GDM scenarios with massive metastable charged sparticles at the LHC.**
J.R. Ellis, A.R. Raklev and O.K. Øye,
JHEP **0610** (2006) 061 [arXiv:hep-ph/0607261].

◇ **Same-sign top quarks as signature of light stops at the LHC.**
S. Kraml and A.R. Raklev,
Phys. Rev. D **73** (2006) 075002 [arXiv:hep-ph/0512284].

◇ **Invariant mass distributions in cascade decays.**
D.J. Miller, P. Osland and A.R. Raklev,
JHEP **0603** (2006) 034 [arXiv:hep-ph/0510356].

Exp. notes

◇ **Measuring massive metastable charged particles with ATLAS RPC timing information.**
J.R. Ellis, A.R. Raklev and O.K. Øye,
ATLAS Public Note, ATL-PHYS-PUB-2007-016.

Thesis

◇ **Supersymmetric cascade decays at the LHC.**
A.R. Raklev,
http://hdl.handle.net/1956/2301

Preprints

◇ **Constraining the MSSM with Dark Matter indirect detection data.**
A. R. Raklev and M. J. White,
CAVENDISH-HEP-2009-23, e-Print: arXiv:0911.1986 [hep-ph]

Proceedings & reports

◇ **New Physics at the LHC. A Les Houches Report.**
G. Brooijmans *et al.*,
CERN-PH-TH-2010-096, arXiv:1005.1229 [hep-ph].
Proceedings of the 5th Les Houches Workshop on Physics at TeV Colliders.

◇ **Cosmic Ray Signatures from Decaying Gravitino Dark Matter.**
N.-E. Bomark, S. Lola, P. Osland and A. R. Raklev,
PoS E **PS-HEP2009** (2009) 098 [arXiv:0911.3571 [hep-ph]].
Proceedings of the EPS HEP 2009 Conference, 16–22 July 2009.

◇ **Physics Beyond the Standard Model: Supersymmetry.**
M.M. Nojiri *et al.*
FERMILAB-CONF-08-082-E, arXiv:0802.3672 [hep-ph].
Proceedings of the 5th Les Houches Workshop on Physics at TeV Colliders.

◇ **Collider aspects of flavour physics at high Q.**
F. del Aguila *et al.*
Eur. Phys. J. C **57** (2008) 183 [arXiv:0801.1800 [hep-ph]]. Report of Working Group 1 of the CERN Workshop: Flavor in the Era of the LHC.

◇ **Sparticle masses from hadronic decays.**
A.R. Raklev,
J. Phys. Conf. Ser. **110** (2008) 072036 [arXiv:0710.0568 [hep-ph]].
Proceedings of the EPS HEP 2007 Conference, 19–25 July 2007.

◇ **Mass determination in cascade decays using shape formulas.**
B.K. Gjelsten, D.J. Miller, P. Osland and A.R. Raklev,
AIP Conf. Proc. **903**, 257-260 (2007) [hep-ph/0611259].
Proceedings of SUSY'06, 12–17 June 2006.

◇ **Mass ambiguities in cascade decays.**
B.K. Gjelsten, D.J. Miller, P. Osland and A.R. Raklev,
hep-ph/0611080.
Proceedings of ICHEP'06, July 26 – August 2 2006.

◇ **Same-sign top quarks as signature of light stops.**
S. Kraml and A.R. Raklev,
AIP Conf. Proc. **903**, 225-228 (2007) [hep-ph/0609293].
Proceedings of SUSY'06, 12–17 June 2006.

◇ **Tevatron-for-LHC Report: Preparations for discoveries.**
V. Buescher *et al.*
FERMILAB-CONF-06-284-T, hep-ph/0608322.
Proceedings of the Tev4LHC Workshop.

◇ **Les Houches physics at TeV colliders 2005 beyond the standard model working group: Summary report.**
B.C. Allanach *et al.*
SLAC-PUB-11770, hep-ph/0602198.
Proceedings of the 4th Les Houches Workshop on Physics at TeV Colliders.

Allocations sought from the Research Council (in 1000 NOK)

Allocations sought from the Research Council

The amount entered under "Allocations sought from Research Council" must match the corresponding fields in the Funding plan for each year.
The Research Council employs fixed rates for various types of fellowships. To calculate payroll and indirect expenses, see Payroll expenses and rates.

Please make sure that the amount sought from the Research Council conforms to requirements about minimum/maximum funding amount sought set out in the call for proposals.

Payroll and indirect expenses encompass salary and social security costs for R&D personnel taking part in the project and indirect costs related to the performance of the R&D activities, such as rent, administrative support functions, ICT,

Procurement of R&D services
Procurement of R&D services from all sectors (universities and university colleges, research institutes, industry) should be entered here. Purchase of other services should be listed under "Other operating expenses".

Equipment
Depreciation costs for research infrastructure that is to be used in the project but was not obtained using funding from the Research Council should be entered here.

Other operating expenses
All direct project-related costs, i.e. costs for goods and services related to the project (chemicals, consumables, travel, fieldwork, seminars and meetings, data acquisition, dissemination and publication activities, etc.) should be entered

	2014	2015	2016	2017	2018	Sum
Doctoral fellowships		484	999	1030	531	3044
Post-doctoral fellowships						0
Grants for visiting researchers	468	967	999	515		2949
Grants for overseas researchers						0
Researcher positions						0
Hourly-based salary including indirect costs						0
Sum payroll and indirect expenses	468	1451	1998	1545	531	5993
Procurement of R&D services						0
Equipment						0
Other operating expenses	170	340	190	190	20	910
Sum from Research Council	638	1791	2188	1735	551	6903