Suggestions of Bachelor thesis projects in Theoretical Physics

Spring semester 2019

The projects should be seen as suggestions. You are encouraged to contact possible supervisors at the department and discuss all available projects.

Computational Biology and Biological Physics

1. **On the conditions for the existence of conservation laws in systems with a discrete time dynamics, and the resulting effects on the behaviour of its solutions**
   Bo Söderberg (bo.soderberg@thep.lu.se)

2. **A simple model for proteins in crowded environments**
   Anders Irbäck (anders@thep.lu.se)

3. **DNA barcodes**
   Tobias Ambjörnsson (tobias@thep.lu.se)

4. **TBA**
   Carl Troein (carl@thep.lu.se)

5. **Exploring lasso regularization for artificial neural networks**
   Mattias Ohlsson (mattias@thep.lu.se)

6. **Neural network modelling of patient survival**
   Patrik Edén (patrik@thep.lu.se)

7. **The role of membrane proteins in cell reprogramming and stem cells pluripotency.**
   Carsten Peterson (carsten@thep.lu.se), Victor Olariu (victor.olariu@thep.lu.se)

8. **A boolean approach for constructing and analyzing regulatory networks governing cell reprogramming.**
   Carsten Peterson (carsten@thep.lu.se), Victor Olariu (victor.olariu@thep.lu.se)

Theoretical Particle Physics

9. **Playing the Lund violin with Herwig**
   Johannes Bellm (Johannes.Bellm@thep.lu.se)

10. **Fitting the pion mass and decay constant to lattice data**
    Johan Bijnens (Johan.Bijnens@thep.lu.se)

11. **Generating final-states in heavy ion collisions**
    Leif Lönnblad (Leif@thep.lu.se)

12. **Phenomenology of Three-Higgs Doublet models with a family symmetry**
    Roman Pasechnik (Roman.Pasechnik@thep.lu.se)

13. **Significance of heavy vector-like fermions in scenarios Beyond the Standard Model**
    Roman Pasechnik (Roman.Pasechnik@thep.lu.se)

14. **Event generators and light dark matter**
    Stefan Prestel (Stefan.Prestel@thep.lu.se)

15. **Properties of non-minimal Higgs models**
    Johan Rathsman (Johan.Rathsman@thep.lu.se)

16. **QCD color structure**
    Malin Sjödahl (Malin.Sjodahl@thep.lu.se)

17. **Parton shower uncertainties on the top mass**
    Torbjörn Sjöstrand (Torbjorn@thep.lu.se)

1. On the conditions for the existence of conservation laws in systems with a discrete time dynamics, and the resulting effects on the behaviour of its solutions

Contact/supervisor: Bo Söderberg (bo.soderberg@thep.lu.se)
Special prerequisite: Basic mathematical methods and basic computer programming skills (Java or C++) corresponding to FYTA11. Basic theoretical physics corresponding to FYTA12
Language: Swedish or English

The production and transport of various substances in many physical and biological systems can be described using simple non-linear models, such as reaction-diffusion (RD) models. Under certain circumstances these can produce different types of stable patterns.

In one dimension, the patterns obtained in simple models of this type have been shown to display different characteristics for different choices of the particular dynamics. For some choices the patterns become particularly smooth, and this can be attributed to certain integrability properties of the underlying dynamics.

It is not clear to what extent these findings generalize to higher dimensions.

The aim of this project is to investigate this issue, both analytically (using various mathematical tools) and by computer simulations of the systems, with subsequent investigation and classification of the resulting patterns.

2. A simple model for proteins in crowded environments

Contact/supervisor: Anders Irbäck (anders@thep.lu.se)
Special prerequisite: Statistical mechanics corresponding to FYTN02 or FYTN05 and programming experience.
Language: English or Swedish

The interior of living cells is a crowded environment, where macromolecules may occupy 30% of the volume. However, most biophysical studies of proteins are conducted in dilute solutions. A fundamental and long-standing question, therefore, is how macromolecular crowding affects reactions such as protein folding, binding and aggregation. In this project, a simple lattice-based statistical-mechanical model will be used to explore basics of protein folding and protein-protein association in crowded environments.

3. DNA barcodes

Contact/supervisor: Tobias Ambjörnsson (tobias@thep.lu.se)
Special prerequisite: Knowledge in Computational Physics corresponding to FYTN03. Statistical physics corresponding to FYTN05 or FYTN02 is helpful but not required.
Language: English or Swedish

The sequence of base pairs of DNA molecules is the genetic blueprint of any living being. Traditional (Sanger shotgun) sequencing methods are all labour-intense and based on fragmenting the unknown DNA, sequencing each fragment, and then attempting to piece the fragments back together using bioinformatics tools. Recent experimental developments in our collaborator Fredrik Westerlund's, Jonas Tegenfeldt's, and Yuval Ebenstein's labs in Gothenburgh, Lund and Tel Aviv, overcome some of the drawbacks of the traditional approach. This new state-of-the-art method allows direct visualization of unfragmented DNA molecules by utilizing a fluorescent sequence-specific binding molecule, or, so called, DNA melting. These DNA barcodes serve as a coarse-grained representation, fingerprint, of a DNA molecule's sequence.

In this project you will use statistical physics tools to compute DNA barcodes, and hence relate experimental DNA barcodes to underlying DNA sequence. Turning experimental data into a form which can be compared to theory also requires some image analysis. The project is hands-on and you will be working directly with new experimental data.

4. TBA

Contact/supervisor: Carl Troein (carl@thep.lu.se).
Special prerequisite: Programming experience
Language: English or Swedish.

Please contact Carl for discussions.

5. Exploring lasso regularization for artificial neural networks

Contact/supervisor: Mattias Ohlsson (mattias.ohlsson@thep.lu.se)
Special prerequisite: Programming skills. Also it is advisable to have some knowledge of artificial neural networks.
Language: Swedish or English

An artificial neural network (ANN) is a powerful and flexible machine learning tools. It has gained popularity in recent years due to its connection to *deep learning* and its success in image classification problems.

One common problem for all kinds of neural networks is overfitting that typically results in models that works well on the data used to train it, but works bad on yet unseen data. There many ways of reducing overfitting, where so called ”lasso regularization” is one method. Perhaps more used in traditional statistical analysis and not so much in neural networks.

In this project we will use lasso both as a method for avoiding overfitting, but also explore its possibilities to do feature selection.

6. Neural network modelling of patient survival

Contact/supervisor: Patrik Edén (patrik@thep.lu.se)
Special prerequisite: Neural networks, some programming skills
Language: English or Swedish.

An important task in health-care is to assign patients into risk-groups. This can e.g. determine treatment. Artificial neural networks (ANNs) can help to find complex relations between patient data (such as age, biomarkers in blood samples, size of tumour, etc) that create distinct risk groups. ANNs are trained by minimizing an objective function which is related to survival, and many possible such functions exist.

We have recently shown that rank-based objective functions can be used, by implementing a genetic algorithm for ANN training. In this project, we will test other rank-based objective functions, that share some properties with more successful continuous ones.

7. The role of membrane proteins in cell reprogramming and stem cells pluripotency.

Contact/supervisor: Carsten Peterson (carsten@thep.lu.se), Victor Olariu (victor.olariu@thep.lu.se)
Special prerequisite: Theoretical Biophysics corresponding to FYTN05. Also advisable is to have knowledge in Computational Physics corresponding to FYTN03. Programming skills.
Language: English or Swedish

Using computational modeling we would like to identify molecular mechanisms including those resulting from over-expressing membrane proteins governing the cell reprogramming process. In particular investigate how Beta-catenin protein interacts with the transcription factors network controlling pluripotency inside stem cells.

The aim of this project is to develop both deterministic and stochastic dynamical models describing the interactions between membrane proteins and the factors expressed in a stem cell. While transition from one stable state to another models cell reprogramming or differentiation, we would also like to further investigate how cell reprogramming efficiency can be increased by perturbing the system i.e. modifying cell membrane concentrations.

8. A boolean approach for constructing and analyzing regulatory networks governing cell reprogramming.

Contact/supervisor: Carsten Peterson (carsten@thep.lu.se), Victor Olariu (victor.olariu@thep.lu.se)
Special prerequisite: Programming skills. Theoretical Biophysics corresponding to FYTN05. Also advisable is to have knowledge in Computational Physics corresponding to FYTN03.
Language: English or Swedish

It has been shown experimentally that the genes expression inside stem cell are predominantly bimodal. This motivates a Boolean modelling approach. Whereas genes network for embryonic stem cells have been constructed by at least two groups, the resulting networks analysis is lacking. Moreover the Boolean model approach has only been applied to stem cells from embryo data and not to pluripotent cells obtained through reprogramming.

The aims of this project are to analyze existing boolean stem cell networks (stability of steady states, number of attractors etc.) and to apply the Boolean model approach to newly available experimental data on mouse skin cells reprogrammed to a stem cell like state. In this project we also aim at developing in house Boolean network model, therefore programming skills are specifically required.

9. Playing the Lund violin with Herwig

Contact/supervisor: Johannes Bellm (johannes.bellm@thep.lu.se)
Special prerequisite: Theoretical Particle Physics corresponding to FYTN04; some experience with computer programming (e.g. Python or C++)
Language: English

Experiments at the Large Hadron Collider (LHC) at CERN heavily rely on computer simulations to compare data to theoretical models. In order to compare measured and simulated events, it is crucial to model the full final state. This is done in so-called event generators. Two out of three major event generators are currently also developed at Lund University. These computer programs factorize the events in typical energies. One of the last steps in this energy split picture is the formation of measurable hadrons from quarks/gluons. Various models have been formulated to describe this mechanism. The Lund string model (invented here) is used for the event generator Pythia. The event generator Herwig creates hadrons with the so-called cluster model. As apart from the creation of hadrons, also other parts of the simulation are distinct, uniting parts of the simulation can give insights about theoretical uncertainties connected with the models. In this project, these effects of replacing the approaches will be studied and possible adaptions of the parameters describing the models (tuning) might be performed.

10. Fitting the pion mass and decay constant to lattice data

Contact/supervisor: Johan Bijnens (Johan.Bijnens@thep.lu.se)
Special prerequisite: Theoretical Particle Physics (FYTN04)
Language: English or Swedish

At low energies in quantum chromodynamics we can use effective field theories and in particular chiral perturbation theory. Recently we in Lund did a first three loop order calculation, see `http://arxiv.org/abs/arxiv:1710.01901`. We obtained the mass and decay constant to three loop order.

Varying the quark masses cannot be done in the real world however the mass and decay constant can be calculated using lattice QCD. The project consists of taking the available lattice data and trying to fit the expressions at three loop order to them.

A rather high level overview can be found in the section on low-energy constants of he FLAG review, updated version available at `http://flag.unibe.ch/Media?action=AttachFile&do=get&target=FLAG_LECs_webupdate.pdf`

11. Generating final-states in heavy ion collisions

Contact/supervisor: Leif Lönnblad (leif@thep.lu.se)
Special prerequisite: Theoretical Particle Physics corresponding to FYTN04.
Language: English or Swedish

In proton collisions at the LHC the produced final states are well described by so-called event generators, which gives a detailed description of hundreds of hadrons produced. In contrast the collision between Lead ions at the LHC, where tens of thousands of hadrons are produced, the final states is normally described using statistical models based on hydro-dynamics, where mainly averaged properties can be handled.

We are currently developing new event-generator models where the final states of heavy ion collisions are simulated in great detail on the level of individual hadrons. This will allow us to understand better how the very hot and dense system produced in such collisions behaves, and therefore also understand better the equally hot and dense quark-gluon soup that was the universe a couple of microseconds after the Big Bang.

Within this development there are a number of smaller sub-projects that are suitable for a bachelor or master thesis.

12. Phenomenology of Three-Higgs Doublet models with a family symmetry

Contact/supervisor: Roman Pasechnik (Roman.Pasechnik@thep.lu.se)

Special prerequisite: Theoretical Particle Physics corresponding to FYTN04
Language: English

The project concerns analysis of particle spectra, interactions and observable signatures of a class of specific extensions of the Standard Model based upon an additional family symmetry and three Higgs doublets. A potential for explaining the fermion mass and mixing hierarchies in this class of models will be overviewed.

13. Significance of heavy vector-like fermions in scenarios Beyond the Standard Model

Contact/supervisor: Roman Pasechnik (Roman.Pasechnik@thep.lu.se)
Special prerequisite: Theoretical Particle Physics corresponding to FYTN04
Language: English

The project concerns analysis of particle spectra, interactions and observable signatures of a class of specific extensions of the Standard Model based upon an additional family symmetry and three Higgs doublets. A potential for explaining the fermion mass and mixing hierarchies in this class of models will be overviewed.

14. Event generators and light dark matter

Contact/supervisor: Stefan Prestel (Stefan.Prestel@thep.lu.se)
Special prerequisite: Theoretical Particle Physics corresponding to FYTN04, some experience with computer programming (e.g. Python or C++)
Language: English

High-energy particle scattering experiments (such as the ones at the LHC) currently paint the picture that physics beyond the Standard Model is absent. At the same time, astrophysical measurements demonstrate the need for dark matter. There is no contradiction if laboratory experiments simply cannot investigate the necessary signals. This challenge is particularly severe if dark matter is very light, or only interacts with the Standard Model through weakly coupled low-mass force carriers. Beside experimental obstacles, the theoretical modeling of new low-mass force carriers can be intricate: new forces can lead to particle cacsade effects and collective particle production phenomena similar to the those in Quantum Chromodynamics or Quantum Electrodynamics. A detailed treatment of light dark matter phenomena in Event Generator Simulations (such as the Pythia project in Lund) will help in designing new experiments (e.g. the LDMX dark-matter experiment, or neutrino-specialized experiments such as DUNE or ESSnuSB) and allow new searches at the LHC.

In this project, we take steps in assessing the impact of current implementations in the Pythia and Dire simulations, and may calculate and implement easy and not-so-easy extensions of the current simulations. Several different projects within this context are possible, at both the bachelor and master level. Possible directions could be:

- Impact of light dark-matter cascades on jet structure and underlying event measurements at high-energy colliders.
- Impact of light dark matter on measurements at neutrino scattering experiments (Minos, MiniBooNe, DUNE) and dedicated low-energy dark-matter experiments (LDMX, BDX, SeaQuest).
- Shining light on dark matter by modelling the interferences with QED.
- Constructing new dark-matter cascades within the Dire simulation.

15. Properties of non-minimal Higgs models

Contact/supervisor: Johan Rathsman (Johan.Rathsman@thep.lu.se)
Special prerequisite: Theoretical Particle Physics corresponding to FYTN04; some experience with computer programming (e.g. C++ or Java.)
Language: English or Swedish

With the discovery of a Higgs boson at the LHC, one of the main questions to be answered is whether this is *the* Higgs boson of the standard model or it is just one of several Higgs particles. The latter case arises in many extensions of the standard model, such as supersymmetric theories. A generic framework for studying models with extended Higgs sectors is the so called two Higgs doublet model (2HDM). In these models there are not one but five different Higgs particles. The extra Higgs particles can be searched for directly but also indirectly through their effects on the properties of the discovered Higgs particle. There are several different aspects of these 2HDMs that could be studied in a bachelor project. For example, investigating the possibilities of describing so called anomalies in B and K-decays in the most general 2HDM without violating constraints on the extra Higgs bosons from the latest LHC data.

16. QCD color structure

Contact/supervisor: Malin Sjödahl (Malin.Sjodahl@thep.lu.se)
Special prerequisite: Theoretical Particle Physics corresponding to FYTN04. Basic knowledge of group theory or the willingness to work with a project where one does not have time to understand all details. Some experience of C++ or Mathematica depending on project.
Language: English or Swedish

In the strong interaction, QuantumChromo Dynamics, QCD, the force carriers, i.e., the gluons (which correspond to photons in quantum electrodynamics), interact with each other. The interaction is described by the non-Abelian group SU(3). This significantly complicates calculations for particle collisions. Various projects involving theoretical improvements, simulation of colored events at the LHC and implementation of color structures in Mathematica can be imagined.

17. Parton shower uncertainties on the top mass

Contact/supervisor: Torbjörn Sjöstrand (torbjorn@thep.lu.se)
Special prerequisite: Theoretical Particle Physics corresponding to FYTN04; some experience with computer programming (e.g. C++ or Java)
Language: English or Swedish

The top quark is the heaviest fundamental particle that we have discovered so far. It is so short-lived that it cannot be studied as such, but only through its decay products. Some of these are quarks, that again cannot be observed directly, but turn into jets (sprays) of hadrons. Top is produced in pp collisions at the LHC at CERN, but in association with other activity that produces further hadrons that partly overlap with the ones from the top. Therefore a top mass determination becomes quite complicated, and relies on event generators that attempt to describe the production and decay of the top, together with the rest of the full collision process. Uncertainties in these generators translate into uncertainties for the top mass. One of these generators is Pythia, developed in Lund.

In this project we want to study how the reconstructed top mass depends on some choices made in the generator. Specifically we will study the impact of parton showers. This is a process whereby a quark can radiate gluons, similarly to the bremsstrahlung process of photons off an electron, and gluons can branch into more gluons. Such showers broadens jets, and how much broader they become impacts the top mass determination. We will study both the existing Pythia showering machinery and two alternatives available as plugins, Vincia and Dire. Specifically, it would be useful to understand whether they reconstruct different top masses even when they are tuned to give the same seeming jet broadening.