Suggestions of Bachelor thesis projects in Theoretical Physics

Spring semester 2020

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. **Exploring basics of protein droplet formation**
   Anders Irbäck (anders@thep.lu.se)

2. **Assembly of optical DNA maps**
   Tobias Ambjörnsson (tobias@thep.lu.se)

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

4. **Explainable Neural Networks**
   Mattias Ohlsson (mattias@thep.lu.se)

5. **Self-adaptive ANN parameters**
   Patrik Edén (patrik@thep.lu.se)

6. **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)

7. **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

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

9. **Finite volume Feynman Integrals in position space**
   Johan Bijnens (Johan.Bijnens@thep.lu.se)

10. **Squaring VEGAS**
    Rikkert Frederix (Rikkert.Frederix@thep.lu.se)

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

12. **Probing New Physics with primordial gravitational waves**
    Roman Pasechnik (Roman.Pasechnik@thep.lu.se)

13. **Principal Component Analyses of Final States in Heavy-Ion Collisions using Pythia/Angantyr**
    Christopher Plumberg (Christopher.Plumberg@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. **TBA**
    Christian Reuschle (Christian.Reuschle@thep.lu.se)
17. **Simulating a lattice QCD test of the Operator Product Expansion in the vacuum**
    Antonio Rodriguez (Antonio.Rodriguez@thep.lu.se)
18. **QCD color structure**
    Malin Sjödahl (Malin.Sjodahl@thep.lu.se)
19. **TBA**
    Jonas Wittbrodt (Jonas.Wittbrodt@thep.lu.se)

1. Exploring basics of protein droplet formation

Contact/supervisor: Anders Irbäck (anders@thep.lu.se)
Recommended knowledge: Statistical mechanics corresponding to FYTN15 and programming experience. Knowledge in theoretical biophysics and computational physics corresponding to FYTN05 and FYTN03, respectively, is helpful but not required.
Language: English or Swedish

Some so-called intrinsically disordered proteins (which lack a well-defined three-dimensional structure) have the ability to spontaneously form dense liquid-like droplets surrounded by a dilute background, through a sequence-dependent liquid-liquid phase separation process. The aim of this project is to explore basics of protein droplet formation using computer simulations of a simple lattice-based model.

2. Assembly of optical DNA maps

Contact/supervisor: Tobias Ambjörnsson (tobias@thep.lu.se)
Recommended knowledge: Computational Physics corresponding to FYTN03 and programming experience. Statistical physics corresponding to FYTN05 or FYTN15 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. Recent experimental developments in our collaborators' labs allow direct sequence-specific visualization of long pieces of DNA molecules – optical DNA maps. Such maps serve as a coarse-grained representation, fingerprint, of a DNA molecule's sequence. The experimental method utilizes fluorescence microscopy and nano-scale devices.

During extraction of DNA from cells, usually the DNA molecules gets fragmented into pieces of size $10^5 - 10^6$ basepairs. As a consequence, experimental optical DNA maps are typically not complete representations of the chromosomal DNA sequence.

In this project you will develop computational methods for assembling fragmented (noisy) optical DNA maps into full chromosomal maps for bacteria. You will get access new experimental data from state-of-the-art experiments in the field.

3. TBA

Contact/supervisor: Carl Troein (carl@thep.lu.se).

Recommended knowledge: Programming experience
Language: English or Swedish.

Please contact Carl for discussions.

4. Explainable Neural Networks

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

An artificial neural network (ANN) is a powerful and flexible machine learning tool. It has gained popularity in recent years due to its connection to *deep learning* and its success in e.g. image analysis and language processing.

When using neural networks for e.g. medical diagnosis or outcome prediction, it is of vital importance to be able to explain the reasoning behind an advice. Generally this is difficult for non-linear machine learning methods. This topic of unmasking the "black boxes" have become even more important with the present focus on deep learning.

In this project you will explore different methods for explaining the operation of complex neural networks models.

5. Self-adaptive ANN parameters

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

During training of artificial neural networks (ANNs), many "hyper-parameters", such as weight suppression, number of hiden nodes, choice of activation functions, etc., determine a balance between flexibility and generalization ability. Too little flexibility will not allow the ANN to find a good solution. Too much flexibility will make the ANN over-trained on its training data set, and unable to make good predictions on new data.

In practical applications, hyper-parameters tend to be manually set, which is time consuming and may lead to some information leaks and biased final results. We will investigate algorithms that dynamically evolve hyper-parameters during training, without manual interference, to see how they affect final results and computational time.

6. 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)
Recommended knowledge: 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.

7. 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)
Recommended knowledge: 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.

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

Contact/supervisor: Johan Bijnens (Johan.Bijnens@thep.lu.se)
Recommended knowledge: 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`

9. Finite volume Feynman Integrals in position space

Contact/supervisor: Johan Bijnens (Johan.Bijnens@thep.lu.se)
Recommended knowledge: Theoretical Particle Physics (FYTN04) or Mathematical methods in physics (FYTN01)
Language: English or Swedish

In particle physics in higher order calculations one encounters loop integrals. These are usually evaluated in momentum space but for some application position space is more convenient. The project is to study finite spatial volume versus infinite spatial volume using position space methods. The momentum space methods can be seen from the introduction and the one-loop discussion in `http://arxiv.org/abs/1311.3531` and an introduction to Feynman integrals in position space in infinite volume is `https://link.springer.com/article/10.1007%2FBF02729917`. This project requires working with Bessel functions and some numerical integration.

10. Squaring VEGAS

Contact/supervisor: Rikkert Frederix (Rikkert.Frederix@thep.lu.se)
Recommended knowledge: Some experience with computer programming (e.g. C++ or Python)
Language: English

In many areas of physics numerical evaluation of multi-dimensional integrals plays an important role. The go-to method is the VEGAS algorithm, developed by Lepage in the late 1970s and early 1980s. Even today this is still the most-commonly used method for numerical multi-dimensional integration. The method relies on importance sampling, in which the variance of the sampled points is reduced by distributing them according to an approximation of the function to integrate. In the VEGAS algorithm this approximation is a step-wise constant function in which it is assumed that the integrand can be factored over its integration variables, $f(x_1, x_2, \dots, x_3) \simeq f(x_1)f(x_2)\cdots f(x_n)$. This looses information about possible correlations among the integration variables in the importance sampling. The goal of the project is to extend the conventional VEGAS algorithm by including 2-dimensional correlations in the importance sampling.

11. Generating final-states in heavy ion collisions

Contact/supervisor: Leif Lönnblad (leif@thep.lu.se)
Recommended knowledge: 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. Probing New Physics with primordial gravitational waves

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

The recent discovery of a binary neutron star merger, firstly observed by the gravitational-wave (GW) interferometers of the LIGO-Virgo collaboration, a new era of multi-messenger astronomy has begun. Furthermore, the reach of GW observatories is by no means exhausted and larger sensitivities are designed for future space-based interferometers such as those of the planned LISA experiment, as well as such proposals for future missions as "ultimate DECIGO" and BBO. This opens up the door for a plethora of new studies including connections with both cosmology and particle physics. In particular, the potential observation of a stochastic GW background produced by violent processes in the early Universe, e.g. by expanding and colliding vacuum bubbles associated with strong cosmological phase transitions, may well become a gravitational probe for beyond-the-Standard Model (BSM) physics and a complement for collider experiments. This project is aimed at the analysis of simple scalar extensions of the Standard Model and first-order phase transitions in their vacua establishing their connections with possibly observable GW signatures.

13. Principal Component Analyses of Final States in Heavy-Ion Collisions using Pythia/Angantyr

Contact/supervisor: Christopher Plumberg (Christopher.Plumberg@thep.lu.se)
Recommended knowledge: FYTN04 and some programming experience (C++ or Python) *Language:* English

Description: Principal Component Analyses (PCAs) are typically applied to two-particle momentum-space correlations in heavy-ion collisions in order to isolate the most important, independent fluctuation modes present in the final states of these collisions. The analyses can be applied to various observables, including multiplicity and anisotropic flow distributions, and provide non-trivial tests for both hydrodynamic and non-hydrodynamic event generators. The proposed project will develop the C++/Python code necessary to integrate the Pythia/Angantyr event generator with a standard PCA which can be compared with experimental equivalents of the same analysis. This can provide valuable insights into the initial-state correlations, the space-time evolution, and the hadronization process in heavy-ion collisions as modeled within this framework.

References: arxiv/nucl-th:1906.08915 and references therein.

14. Event generators and light dark matter

Contact/supervisor: Stefan Prestel (Stefan.Prestel@thep.lu.se)
Recommended knowledge: 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, Mini-BooNe, 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)
Recommended knowledge: 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 constraints on the most general 2HDM from charged lepton flavour violating decays, the electric dipole moment of the electron and the anomalous magnetic moment of the muon.

16. TBA

Contact/supervisor: Christian Reuschle (Christian.Reuschle@thep.lu.se)
Recommended knowledge: Theoretical Particle Physics corresponding to FYTN04;
Language: English

17. Simulating a lattice QCD test of the Operator Product Expansion in the vacuum

Contact/supervisor: Antonio Rodriguez (Antonio.Rodriguez@thep.lu.se)
Recommended knowledge: Theoretical Particle Physics corresponding to FYTN04;
Language: English

At low energies, a description of strong interactions in terms of approximately free quarks and gluons (perturbative QCD) is not valid. An extension of perturbative QCD, the so-called Operator Product Expansion (OPE) in the vacuum, is known to extend the applicability of it at intermediate energies.

In this project, it would be shown how, by comparing the well-known OPE of one specific mathematical object, the so-called vector-tensor (VT) correlation function, with potential lattice data, one may perform a unique test of the validity of the OPE and obtain the so-called quark-gluon condensate with an unprecedented precision. First, fake lattice data would need to be generated under different assumptions for, subsequently, compare it to the OPE prediction.

18. QCD color structure

Contact/supervisor: Malin Sjödahl (Malin.Sjodahl@thep.lu.se)
Recommended knowledge: 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.

19. TBA

Contact/supervisor: Jonas Wittbrodt (Jonas.Wittbrodt@thep.lu.se)
Recommended knowledge: Theoretical Particle Physics corresponding to FYTN04;
Language: English