IFJ PAN Particle Physics Summer Student Programme

Projects 2022

Projects will be done in pairs.

1 Remote Participants

Please note that the following 5 projects are available only for the remote participants.

1. **Background estimation from fake taus in double boson Higgs production with leptons in a final state.**

   Supervisor: dr Bartłomiej Żabiński
   The ATLAS Experiment Department (NZ14), Bartlomiej.Zabinski@ifj.edu.pl

   Discovering the Higgs boson was the Holy Grail of LHC experiments. Since its discovery in 2012 the Higgs boson has been produced copiously and detected using various decay channels by the ATLAS and CMS experiments. Theory predicts that not only single Higgses, but also double Higgs bosons are produced in a single proton-proton collision! In some of these events the two Higgs bosons originate from the splitting of a single Higgs. Measuring the strength of these self-interactions will cast light onto the electroweak symmetry breaking.

   Double Higgs production is extremely rare. It requires sophisticated experimental techniques and analyzing many decay channels in order to observe signal events. In the ATLAS experiment searches of double Higgs production were done mostly in channels with b quarks (see Fig 1), but a very recent idea adopted by the ALTAS experiment is to search for double Higgs events through its various leptonic decays. In this analysis, we do not distinguish if any of the Higgses decays to Z, W bosons, or τ leptons but use all these processes at once to detect as many events as possible.

   In your task, you will use data events collected by the ATLAS experiment, and those generated by Monte Carlo programs. The aim is to estimate one of the important backgrounds in a channel with single lepton tau in the final state. The background is from tracks that were reconstructed as taus by algorithms but they are not real taus. To perform this task you will learn data-driven techniques and use the ROOT framework, to write scripts in Python or C++. During this project, you will get acquainted with the work in the ATLAS Collaboration and will develop your programming skills.

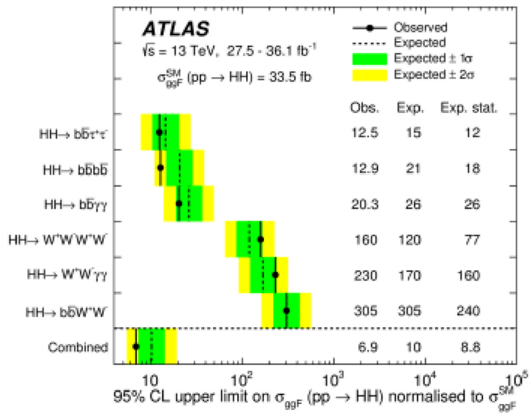


Figure 1. Upper limits at 95% CL on the cross-section of the $gg_{FSM}HH$ production normalised to its SM expectation $\sigma_S M^{ggF}$ ($pp \to HH$) from the $b\bar{b}\tau^+\tau^-$, $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $W^+W^-W^+W^-$, $W^+W^-\gamma\gamma$ and $W^+W^-b\bar{b}$ searches, and their statistical combination. The column "Obs." lists the observed limits, "Exp." the expected limits with all statistical and systematic uncertainties, and "Exp. stat." the expected limits obtained including only statistical uncertainties in the fit. (Phys. Lett. B 800 (2020) 135103).

2. **Unsupervised classification of particle interaction events using deep neural network**

   Supervisor: dr hab. Marcin Wolter, dr Rafał Staszewski
   The ATLAS Experiment Department (NZ14), Marcin.Wolter@ifj.edu.pl, rafal.staszewski@ifj.edu.pl

   Machine learning is often used in particle physics for the classification of events. The goal of the project is to attempt an unsupervised classification of events, where no information about the type of event is used. The proposed approach is based on an Deep Neural Network (DNN) auto-encoder for the dimensionality reduction together with a clusterisation algorithm. The procedure starts with Monte Carlo event generators, which are used to produce samples of artificial, pseudo-random events, which are later used for DNN training.

   The project will be performed using the Google Colab environment with Tensorflow, Keras and scikit-learn libraries. A good understanding of Python programming is needed.

3. **Search for earthquake precursors with cosmic rays detection**

Supervisor: dr David Alvarez-Castillo
Department of Cosmic Ray Research and Neutrino Studies (NZ15), dalvarez@ifj.edu.pl

The goal of this project is to perform a dedicated search for earthquake precursors with cosmic rays data as well as from seismic detection. Recently, a correlation which is presumably indicative of a precursor has been found, as reported in arXiv:2204.12310. Within this study we shall consider similar analyses to those presented there as well as Bayesian methods aiming at finding changes in modulation of the signals before earthquake occurrence.

4. **New physics searches in ultra-peripheral collisions in ALICE**

Supervisor: dr hab. Adam Matyja
Department of the Ultra-relativistic Nuclear Physics and Hadron Interactions (NZ23), adam.tomasz.matyja@cern.ch

The ALICE experiment is one of big experiments at the Large Hadron Collider (LHC) at CERN. It has been designed to study Quantum Chromodynamics (QCD) in dense environment, where thousands of particles are observed, and sparse environment with just few of them. ALICE has collected data coming from Pb-Pb collisions at the centre-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 5.02$ TeV for different centrality classes. The central collisions are head-on collisions with the largest nuclei overlap. There is little overlap of two nuclei in peripheral collisions. The distance between two nuclei is larger than a sum of their radii in the ultraperipheral collisions (UPCs). UPCs provide a clear environment for studies photoproduction mechanisms. One of the processes of particular interest is the tau lepton pair photoproduction in Pb-Pb UPC. The cross section for this process scales with Z^4, however, it is also suppressed by α_{EM}^2 (α_{EM} is the fine structure constant). The difficulties related to tau leptons are coming from the fact that they decay quickly and cannot be observed directly. Moreover, they decay with at least one neutrino. What is particularly interesting in the tau lepton pair production, is the fact that this process is sensitive to the new physics hidden in the anomalous magnetic moment of tau lepton (a_τ). A measurement of tau lepton pair production can be used to constrain a_τ. The best experimental measurement of a_τ comes from DELPHI experiment and is $a_\tau = -0.018(17)$. However, Standard Model theoretical calculations are way more precise $a_\tau^{th} = 0.00117721(5)$. Recently, tau pair production was observed in CMS and ATLAS experiments with just few hundreds of events in data coming from Run 2. The similar statistics is expected in ALICE, which has an excellent low momentum particle tracking.

Students will perform ROOT based analysis of ALICE data coming from the UPCs of Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV during Run 2. Data are going to be compared to Monte Carlo predictions.

5. **Event-by-event correlations and fluctuations with strongly intensive quantities in p-Pb collisions with ALICE @CERN**

Supervisor: dr Iwona Sputowska
Department of the Ultra-relativistic Nuclear Physics and Hadron Interactions (NZ23), Iwona.Sputowska@ifj.edu.pl

The term ultra-relativistic heavy-ion collisions refers to the interaction between two heavy atomic nuclei (e.g., Pb) with energies of at least a few GeV per nucleon. In the ALICE (A Large Ion Collider Experiment) at the LHC, the collision energy is sufficient to create a new form of matter called the Quark-Gluon Plasma (QGP) under laboratory conditions. However, this new state of matter, which forms early in the ultrarelativistic ion collision, cannot be directly detected. A hot and dense but rapidly expanding system of quarks and gluons quickly freezes into the final hadron states we measure in detectors.

An insight into the early stages of the nuclear-nucleus collision can be provided by analysing event-by-event particle correlations and fluctuations. In general, correlations and fluctuations characterize the properties of a physical system. They can be sensitive to phase transitions of nuclear matter. Therefore, over the years, they have become a standard tool for studying the properties of strongly interacting matter at high energies.

The strongly intensive quantity $\sum$ is a relatively new observable of correlation and fluctuations of the system, introduced recently to the domain of heavy-ion physics. In superposition models of heavy-ion collision, which assume independent particle production from statistically identical sources, $\sum$ is insensitive to the number of sources and their fluctuations. Therefore, it provides direct information on a single source's multiplicity correlations and fluctuations.

Your task will be to obtain the first ever results on the strongly intensive quantity $\sum$ in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the ALICE experiment at the LHC.

2 Local Participants

Please note that the following 15 projects are available only for the local participants.

1. **Study of semi-inclusive characteristics of B decays at Belle experiment**

   Supervisor: dr Jarosław Wiechczyński
   Department of Leptonic Interactions (NZ11), wiechczynski@belle2.ifj.edu.pl

   Study of the decays of B mesons is one of the most crucial fields to search for physics beyond the Standard Model (SM). A large majority of B decays are the processes governed by $b \to c$ quark transitions, whose theoretical predictions for the inclusive decay rates are very accurate, however, experimentally measured exclusive B decays do not fill out the predicted inclusive value. In particular, the inclusive $B \to D_s X$ decays (X stands for one or more undefined particles in the final state) are relatively poorly understood, especially in case D_s meson is produced in the so called "lower vertex" on the Feynman diagram.

   In this exercise we will exploit the unique experimental features of "B-Factories" in which two B mesons are produced exclusively in the $e^+e^- \to Y(4S)tob\bar{b}$ process, so the full reconstruction of one B meson (so called "tagging B") allows to perform (semi-)inclusive measurement of the other B.

   Working on the real data collected by the Belle experiment we will try to estimate the branching ratio of the $B \to D_s X$ process for the D_s meson produced in both lower and upper vertex. We will also take a look at the inclusive characteristics of such decays.

2. **Study of Lepton flavour violating decays in Belle2**

   Supervisor: mgr Junaid Ur Rehman, dr hab. Andrzej Bożek
   Department of Leptonic Interactions (NZ11), junaid.rehmanifj.edu.pl, bozek@belle2.ifj.edu.pl

   Our visible universe at its most fundamental level is best described by the Standard Model(SM) of particle physics. Despite its huge successes in explaining all the basic material ingredients(Leptons and quarks) and three(Strong, Electromagnetic and weak) basic interactions between them, it is unable to explain certain phenomenons e.g matter antimatter asymmetry, dark energy, dark matter, gravity etc. So there must be some New Physics(NP) beyond the SM. One way to check the NP is to search for the particle decays which are forbidden by the SM. One class of such decays is known as the lepton flavor violating(LFV) decays. In LFV decays, Lepton number is violated which must be strictly conserved according to the SM.

   In this internship we will examine one of the LFV decay $B_0 \to K^* e^\pm \mu^\mp$. By using the data from Belle and Belle2 detector, we will calculate the signal branching fraction of this decay. During the project we will learn to use the important software tools(mainly Monte Carlo generation, event reconstruction and analysis) used in modern high energy physics. And the preference is only those students who are locally available here at the institute. Kindly update it there or send me the link which contain the modification of topics.

3. **Measurements of the depletion voltage of the SOI pixel detector**

   Supervisor: dr inż Piotr Kapusta
   Department of Leptonic Interactions (NZ11), Piotr.Kapusta@ifj.edu.pl

   Students gather knowledge about operational principles of the Silicon On Insulator particle pixel detectors. Using available equipment they write their own software for processing the detector signal. Developed software is next used in a series of measurements at different detector bias. Based on the obtained results a precise value of the detector depletion voltage together with other parameters are determined.

4. **Particle showers in ATLAS Forward Proton detectors**

   Supervisor: dr Maciej Lewicki
   The Diffractive Physics Department (NZ13), maciej.piotr.lewicki@cern.ch

   ATLAS Forward Protons (AFP) is a set of detectors placed approximately 200 m from the collision point, dedicated to register protons that remain intact after the interaction, in so called "diffractive events". However, the AFP registers not only the diffractive protons, but also particles that originate from interaction with detector material (showers). The aim of this project is to study the properties of collected data, searching for ways to identify and quantify the contribution from particle showers.

5. **Elastic scattering analysis in 1D and 2D**

Supervisor: dr Rafał Staszewski, mgr Ferhat Ferhat Öztürk
The Diffractive Physics Department (NZ13), rafal.staszewski@ifj.edu.pl, ferhat.ozturk@ifj.edu.pl

Elastic scattering is kinematically the simplest type of proton-proton interactions at the LHC. When the beams are unpolarized, there is only one non-trivial kinematic parameter characterizing the interaction – the scattering angle, $\theta = \sqrt{\theta_x^2 + \theta_y^2}$. Contrary to the simple kinematics, the dynamics of this process is quite complex, with several mechanisms contributing to the final shape of the θ distribution. The azimuthal angle φ has a uniform distribution and does not carry any information about the dynamics. However, the experimental setup affects the measurements in the horizontal and vertical directions differently: the acceptance and the resolution is different for θ_x and θ_y.

The goal of the project is to prepare a simple Monte Carlo simulation of an elastic scattering experiment at LHC and compare two analysis strategies for extracting the underlying parameters describing the shape of the θ distribution. The first strategy will involve a one-dimensional fit to the θ distribution. The second strategy will attempt a two-dimensional fit to the (θ_x, θ_y) distribution.

The project requires decent programming skills in C++ or Python.

6. **Exploring b-jet properties in Pb+Pb collisions with the ATLAS experiment at the LHC**

Supervisor: prof. dr hab. Adam Trzupek
The ATLAS Experiment Department (NZ14), Adam.Trzupek@ifj.edu.pl

The purpose of ultra-relativistic lead ion collisions is to create a hot and dense medium, quark-gluon plasma (QGP), a state of matter that existed in the early universe and is believed to be present in the cores of neutron stars. In heavy-ion collisions at high LHC energies, the quark and gluons, basic components of the nucleons, not only form QGP but some of them are subject to strong interactions with large momentum transvers through gluon exchange, the so-called hard scattering. As a result of these scatterings, jets are formed. Jet is a stream of particles collimated in a narrow cone. As jets interact strongly with the opaque QGP, their energies and shapes measured in the detector change significantly. This jet-medium interaction makes them one of the most useful tools for studying the properties of the QGP matter.

The aim of the project is to investigate the properties of jets containing particles composed of heavy-flavour quarks (b, c), in Pb+Pb collisions. Charm and beauty quarks, due to their large masses, are formed at an early stage of heavy ion collisions and lose less energy than light quarks and gluons when passing through QGP. In this project, b-jet MC simulations in the ATLAS environment will be used to study and visualize the details of the b-hadron decay chains.

Programming framework: C++, ROOT.

7. **Three approaches to B-jet identification in ATLAS experiment from easy to hard**

Supervisor: dr Dominik Derendarz
The ATLAS Experiment Department (NZ14), dominik.derendarz@ifj.edu.pl

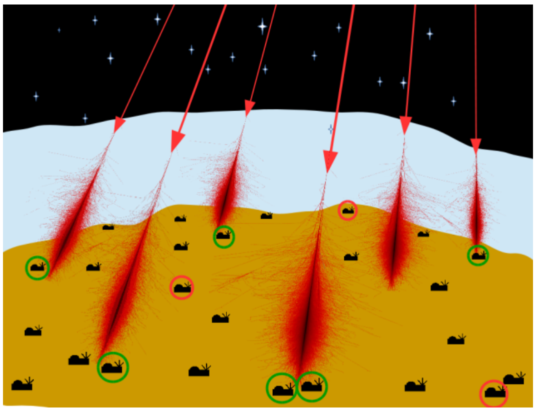
Heavy ion collisions at the LHC provide a unique opportunity for the study of the matter at the extreme conditions. For the brief moment after collision of two lead nuclei their constituents form a system with very high temperature and energy density. These conditions allow for the phase transition to the quark-gluon plasma (QGP) state which then cools down and goes back to the hadronic matter state that we can observe in the detector. Independently of the QGP formation, the hard scattering of quarks or gluons is very likely to happen in the heavy ion collision. The products of this hard interaction will then evolve in the presence of the QGP medium that will typically lead to reduction of their initial energy. The details of the energy loss mechanism is one of the most interesting open questions in the heavy ion physics field right now.

To address this question our group in the ATLAS experiment department is working on the measurement of the productions of b-jets., i.e. the collimated group of particles originating from a single parton, in this case a b-quark. During this project we will have a closer look at possible ways to identify b-jets. Staring with quite easy approach that relies on the identification of muon that originates from the decay of b-hadron, then moving to more advanced technique using reconstruction of secondary decay vertex of b-hadron and finally we will use a deep feed-forward neural network to identify b-jets. Each of the methods have some pros and cones, we will try to have a look at them using MC simulation and some real data from 2018 Pb+Pb run at LHC.

8. **Detection of cosmic-ray photons**

Supervisor: dr hab. Krzysztof Woźniak
The ATLAS Experiment Department (NZ14), Krzysztof.Wozniak@ifj.edu.pl

The cosmic rays since their discovery have provided valuable information and discoveries. Even now the particles with highest energies are not those studied in laboratories and obtained form accelerators, but form the cosmic rays. Particles with highest energies are rare, so to detect them large observatories, like Auger Observatory, are build.
However, new phenomena may manifest themselves not as a single particle, but as correlated ensembles of cosmic rays. If their origin point is far from the Earth they may arrive to the Earth in places hundreds km apart.
Especially, it is predicted that particles traversing the magnetic field of the Sun may generate bunches of photons. The CREDO project aims to combine data from all available detectors, including even individual smartphones, to find Cosmic-Ray Ensembles.

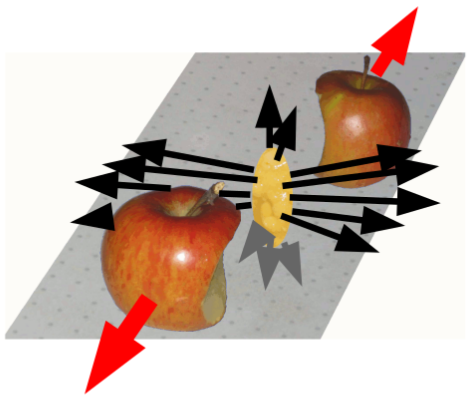


Currently the development of reconstruction methods is necessary. The project for Summer Student Programme will include analysis of simulations of cosmic ray cascades. They are preformed using KASCADE program which provides detailed information on the interaction of a primary cosmic particle and the production of a full cascade of secondary particles. There is a difference between cascades initiated by photons and by charged particles. In this project we will try to determine if it is possible to identify the type of particle using a system of simple detectors.

9. **Heavy-ion collisions at the LHC with the ATLAS detector**

Supervisor: dr hab. Krzysztof Woźniak
The ATLAS Experiment Department (NZ14), Krzysztof.Wozniak@ifj.edu.pl

The ATLAS detector is used in one of four experiments working at Large Hadron Collider at CERN, which accelerates beams of particles to the highest energies available in laboratories. Most of the time beams of protons are collided, however collisions of nuclei are also possible.
In the collisions of nuclei at the extreme energies a new type of matter, Quark-Gluon Plasma (QGP), is created. In QGP its components, quark and gluons, are no more confined in hadrons but are released and strongly interact within the QGP forming an almost perfect fluid with very low viscosity. This leads to collective effects which are observed in heavy-ion collisions.



During the three weeks of practical part of the Summer Student Programme the data from the ATLAS experiment will be analyzed. The collisions of xenon nuclei will be studied with the aim to find signs of QGP.

10. **Search for cosmic-ray ensembles signatures with CORSIKA simulations**

Supervisor: dr Oleksandr Sushchov
Department of Cosmic Ray Research and Neutrino Studies (NZ15), oleksandr.sushchov@ifj.edu.pl

Cosmic rays interact with the molecules of atmospheric gases producing cascades of secondary particles named extensive air showers (EAS). The latter are registered by terrestrial detectors and thus the parameters (energy, arrival directions etc.) of the primary particles are estimated. The state-of-the-art approach to cosmic ray investigations rests on the single EAS, while several years ago the Cosmic-Ray Extremely Distributed Observatory (CREDO) Collaboration initiated a scientific program based on a novel idea of cosmic ray research. It is dedicated to the study of cosmic-ray ensembles (CRE), the groups consisting of at least 2 cosmic rays originated by the same parent particle wherever in the Universe and thus correlated in time and/or in space. CREDO paradigm allows for testing already existing physics scenarios, both classical and exotic, but, at the same time, is prepared for yet unknown, "new physics".

Using CORSIKA, a widely used code for simulations of EAS, we are going to study the footprints of the latter, in order to define the conditions favourable to the registration of CRE and thus to justify the concept of the CREDO program, which might have a great impact on the cosmic-ray astrophysics.

11. **Reconstruction of particle tracks using Deep Neural Networks**

    Supervisor: dr hab. Marcin Wolter
    The ATLAS Experiment Department (NZ14), Marcin.Wolter@ifj.edu.pl

    Image classification using Deep Neural Networks (DNN) is a rapidly developing part of computer science. The techniques developed for various applications become also used in High Energy Physics, presently mostly for event classification. In the recent years the novel methods of particle track reconstruction using DNNs are being developed. In the recent years the Graph Neural Networks (GNNs) are becoming a popular tool allowing fast and efficient track reconstruction.

    The task would be to test the performance of the GNN network first on a very simple toy detector model. In the next step the GNN algorithm should be used for track finding in a simplified MuonE experiment detector. The tracking performance should be measured.

    The project should be implemented using the Google Colaboratory http://colab.research.google.com, which allows creating iPython notebooks and offers free access to Graphic Processor Units (GPU), which speed up the network training. Therefore, the candidate should be willing to use the python language and to have the Google ID to be able to use the resources supplied by them.

12. **Study of neutrino interactions in the T2K experiment**

    Supervisor: dr Tomasz Wąchała
    Department of Cosmic Ray Research and Neutrino Studies (NZ15), Tomasz.Wachala@ifj.edu.pl

    T2K is a neutrino experiment designed to investigate how neutrinos change from one flavour to another as they travel (neutrino oscillations). The major scientific goal of T2K is the search for CP violation in the neutrino oscillations. This task requires a precision measurement of the electron neutrino (antineutrino) appearance probability in the muon neutrino (antineutrino) beam. The main contribution to the systematic uncertainty in this measurement comes from the mis-modelling of neutrino interactions. The group of scientists from IFJ PAN participates in the neutrino cross section measurements using the T2K near detector ND280. That measurements should help us to better understand the neutrino interactions.

    The aim of the project will be the improvement of the selection methods of various neutrino interaction channels in the ND280 detector and the analysis of the selection quality. The application of the multi-variate analysis techniques (neural networks, BDTs etc.) and machine learning to the selection process is also possible.

13. **Space-time evolution of charged muons interacting with spectators in heavy-ions collisions**

    Supervisor: dr hab. Katarzyna Mazurek
    Department of Theory of Strong and Multiple-body Interactions (NZ21), Katarzyna.Mazurek@ifj.edu.pl

    The collision of heavy ions with relativistic or ultra-relativistic velocities produces the very dense matter means the quark-gluon plasma and some remnants. The nuclei, which after collision lose part of their matter, could have quite big temperature and excitation energy. They also generate the electromagnetic field around them. In this conditions some particles are created in the QGP or in space around by virtual photons interactions. The subject of the project is an estimation of the space-time evolution of produced charged muons. They interact with the positively charged nuclei and their trajectories are influenced by Coulomb repulsion/attraction forces. The codes are lately used for verification of behaviour of electrons and positrons in presence of nuclei and some calculation was already done for muons emitted from the QGP, thus the background is well known. The project is purely theoretical but the outcome could be verified soon by LHC experiments.

14. **Search for critical signatures of strongly interacting matter in heavy ion collisions in SHINE @ CERN SPS**

    Supervisor: dr Nikolaos Davis
    Department of the Ultra-relativistic Nuclear Physics and Hadron Interactions (NZ23), nikolaos.davis@ifj.edu.pl

The critical point (CP) of strongly interacting matter is an important hypothesized feature of the phase diagram of Quantum Chromodynamics (QCD) – the plot in temperature and baryon density that maps the states of strongly interacting matter (nuclear matter, hadron gas, quark-gluon plasma) and the phase transitions between them. Experimental detection of the CP and its exact location and characteristics is a highly sought-after goal of high-energy ion collision experiments in large particle accelerators, such as the SPS and LHC at CERN.

In this project, we will be looking for critical point signatures in medium-size ion collision data at SPS energies ($\sqrt{s_{NN}} \sim 10$ GeV) collected by the SHINE experiment Collaboration. We will focus on the critical observable of proton density fluctuations, probed via the method of intermittency analysis of factorial moments of proton transverse momenta. Analysis is multifold, including, first, the selection and filtering of experimental data from the SHINE record of collected events; the calculation of second scaled factorial moments (SSFMs) of proton transverse momenta from the data, and the estimation of their uncertainties; and the generation and evaluation of simple Monte Carlo simulation models of critical protons and their background. Comparison with models is important in order to determine whether intermittency (scaling of factorial moments) is compatible with the patterns present in experimental data, and therefore whether the data signify an approach to the CP.

15. **Exploring Jet quenching in relativistic heavy ion collisions**

Supervisor: dr Souvik Priyam Adhya
Department of Particle Theory (NZ42), souvik.adhya@ifj.edu.pl

Background and motivation:
Comprehending the physics of strong interaction in the realm of hot and dense systems, such as the early Universe, is currently at the zenith of interest among researchers all over the world. Collisions of heavy nuclei at the largest particle accelerators on Earth, especially the CERN LHC (Large Hadron Collider), provide optimal conditions for the production and investigation of matter under such extreme conditions of temperature (150-160 MeV) and density (0.4-1 GeV / fm3). In these conditions, a phase transition from ordinary matter to a new state of matter, the quark-gluon plasma (QGP), is expected to happen. Quantum chromodynamics (QCD) – the theory that describes interaction of elementary particles: quarks, gluons commonly called partons, and how they form hadrons, provides the theoretical framework to encapsulate such studies. The "hard probes" are a precise class of probes, among which "jets", hadronic sprays created during the process of fragmentation of highly energetic quarks and gluons can be used as a diagnostic tool to study the properties of QGP. In particular, in-depth theoretical and phenomenological analysis of "jet quenching" is one of the promising ways to do such a study.

Methodology:
We shall start specifically by solving the in medium (QGP) gluon evolution equation to arrive at the medium evolved gluon spectra for the case of static medium. For our purpose, we shall solve this differential equation numerically through Python programming. In addition, we shall compare the numerical result to the analytical solution of the medium evolved gluon spectra obtained for the soft momenta case.

Future scope: One can utilize the numerical solutions medium evolved gluon spectra to calculate the nuclear modification factor for inclusive jets and compare with the data from ATLAS, LHC.

Suggested reading and reference:
– https://arxiv.org/abs/1911.12193
– https://arxiv.org/abs/1811.06390

Essential skills: Programming in Python.
Desirable skills: Basic understanding of Quantum mechanics and Particle Physics.