

Keemilise ja Bioloogilise Füüsika Instituudi (KBFI) teemad

Topics from National Institute of Chemical Physics and Biophysics (NICPB)

* Need teemad ei ole kohustuslikud. Kui üliõpilane soovib, siis võib ise leida teema ühes juhendajaga, mis on sobilik praktikaks või lõputööks.

* Using these topics is not obligatory. If the student wishes then the student could find a topic and a supervisor by himself/herself, which are suitable for internship or graduation theses.

Gravity, Black Holes and the Early Universe

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Annotation. Gravity shapes the Universe, from the motion of planets to the formation of black holes and the expansion of space itself. Einstein's general theory of relativity provides a framework for understanding these phenomena, while also raising fundamental questions about the origin of the Universe and the limits of our understanding of space and time.

Students will explore selected topics in gravitational physics and cosmology through analytical calculations and numerical methods. Possible projects include studying the motion of particles and light around black holes and investigating cosmic inflation. Topics can be adapted for internships and bachelor's or master's theses, ranging from an introduction to general relativity and cosmology to more advanced research questions. The working language is English, <https://kbfi.ee/high-energy-and-computational-physics/?lang=en>

Expectation for candidate. Interest in gravity, black holes or cosmology, basic knowledge of calculus and differential equations, and willingness to learn and work independently. Prior knowledge of general relativity or cosmology is welcome but not required.

Astro-osakestefüüsika / Astro-particle physics

Gert Hütsi (gert.hutsi@to.ee)

Teema tutvustus. Astro-osakestefüüsika on osakestefüüsika ja astrofüüsika ühine uurimisvaldkond. Peamine tegevus on uute kosmiliste füüsikanähtuse otsimine ja nende seletamine osakestefüüsika raames. Seetõttu peab kogenud astro-osakestefüüsik tundma hästi nii osakeste- kui astrofüüsikat ja tundma suurt hulka väga erinevaid eksperimente optilistest teleskoopidest gammakiirguse teleskoopideni tehiskaaslastel, maa-alustest tumeaine detektoritest gravitatsioonilainete detektoriteni. Meie uurimisrühm on väga rahvusvaheline ja töökeeleks on inglise keel, <https://hep.kbfi.ee/>.

Nõuded kandidaadile. Huvi osakeste- ja astrofüüsika vastu, mõningad teadmised matemaatikast (diferentsiaalvõrrandid), andmeanalüüsist (Python) ja statistikast, võime ise õppida ja koostööd teha.

Annotation. Astro-particle is a joint research field between particle physics and astrophysics. The main activity is looking for new hints of new physical phenomena in space and explaining the phenomena in the framework of particle physics. Thus an astro-particle physicist has to handle both particle and astro-physics well and also should have very wide understanding of very different experiments: from optical telescopes to gamma-ray satellite telescopes, from underground dark matter direct detection experiments to gravitational wave telescopes. Our research group is very international and the working language is English, <https://hep.kbfi.ee/>.

Expectation for candidate. Interest in particle physics and astrophysics, some skills in mathematics (differential equations), data analysis (Python) and statistics, strong self-learning and collaborative working abilities.

Ekspérimentaalne osakestefüüsika CERN-i CMS detektori juures / Experimental particle physics at the CMS experiment at CERN

Mario Kadastik (mario.kadastik@cern.ch)

Teema tutvustus. CMS (Compact Muon Solenoid) on CERN-is LHC kiirendi juures asuv universaalne osakestedetektor, kus otsitakse uusi osakesi ja tehakse tuntud osakestefüüsika täppismõõtmisi. CMS on üks CERN-i ja terve maailma suuremaid osakestefüüsika eksperimente. Tallinna CMS-i töörühm tegeleb eksperimendi andmete modelleerimise ja analüüsiga. Meie töörühm on rahvusvaheline ja töökeeleks on inglise keel, <https://hep.kbfi.ee/>.

Nõuded kandidaadile. Elementaarsed teadmised erirelatiivsusteooriast, programmeerimisoskused (C++, Python), mõningad teadmised statistikast või masinõppest.

Annotation. CMS (Compact Muon Solenoid) is an universal particle detector at CERN targeting unknown particle physical phenomena and doing many precision measurements in well-established particle physics. CMS is one of a largest particle physics experiments at CERN and in the world. The Tallinn CMS workgroup is focussed on data modelling and analysis at the experiment. Our research group is international and the working language is English, <https://hep.kbfi.ee/>.

Expectation for candidate. Basic understanding in special relativity, skills in programming (C++, Python), some skills in statistics and possibly machine learning.

Kosmoloogia, inflatsioon ja gravitatsioonilained / Particle physics phenomenology

Kristjan Kannike (kristjan.kannike@cern.ch)

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Teema tutvustus. Varajane universum on suurepärane osakestefüüsika laboratoorium. Kosmiline inflatsioon jättis oma jäljed algsetesse aine tihedushäiritustesse ja gravitatsioonilainetesse. Ka kosmilised faasiüleminekud võivad jätta jälgi gravitatsioonilainetesse ja selgitada, miks maailm koosneb ainest, mitte antiainest. Kuna gravitatsioonilainete eksperimendialne uurimine alles algas, on see uus ja väga kiiresti kasvav uurimisvaldkond. Meie rühma koosseis on väga rahvusvaheline; teeme koostööd paljude teadlastega üle terve maailma, <https://hep.kbfi.ee/>.

Nõuded kandidaadile. Huvi osakeste- ja astrofüüsika vastu, mõningad teadmised matemaatikast (diferentsiaalvõrrandid), andmeanalüüsist (Python, Wolfram Mathematica) ja statistikast, võime ise õppida ja koostööd teha.

Annotation. The early Universe is a sensitive laboratory of particle physics. The footprints of the cosmic inflation remain in the initial perturbations of matter and gravitational waves. Cosmic phase transformations can left signs in gravitational waves as well and explain the abundance of ordinary matter. As the experimental research of gravitation field just started, it is a very exciting and fast growing field of research. Our research group is highly international and has collaborators all over the world, <https://hep.kbfi.ee/>.

Expectation for candidate. Interest in particle physics and cosmology, some skills in mathematics (differential equations) and data analysis (Python, Wolfram Mathematica), strong self-learning and collaborative working abilities.

Experimental particle physics at the CMS experiment at CERN

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Annotation. The Compact Muon Solenoid (CMS) is one of the two general-purpose detectors at the Large Hadron Collider (LHC) at CERN. It is designed to study a wide range of physics, from precision measurements of the Standard Model (SM) to searches for new physics such as supersymmetry, dark matter, or extended Higgs sectors. CMS played a central role in the discovery of the Higgs boson in 2012 and continues to be at the forefront of high-energy physics research.

Since 2012 many of the properties of the Higgs boson have been investigated and constrained up to a few percent to be in good agreement with the SM. One notable exception is the trilinear Higgs boson self coupling λ . It can only be directly measured through the study of Di-Higgs (HH) events, the simultaneous production of two Higgs at once.

Studying HH does not only give us insight into λ which is directly related to the Higgs boson potential and the stability of our Universe, but also other SM couplings such as the quartic coupling between two Higgs and two vector bosons C2V, as well as several Beyond-SM (BSM) scenarios studied in effective field theory (for example HEFT with C2, Cg and C2g).

Connected to this, we also can search for resonant production of Higgs boson pairs or other Higgs like particles. These are predicted by many BSM models, such as scenarios with extended Higgs sectors predicting additional Higgs like particles of varying mass for e.g. 2HDM and NMSSM. Extended Higgs sector in BSM models offer rich phenomenology, including modified branching fractions, cascades decays and enhanced production rates, making them ideal for experimental search at the LHC.

Our research group is highly international, with English as the working language (<https://hep.kbfi.ee/>). Students joining us will directly contribute to CMS analyses, gaining hands-on experience with real LHC data, Monte Carlo simulations, and modern analysis frameworks. They will acquire practical skills in Python, ROOT, and advanced statistical and machine learning (ML) techniques, while also benefiting from the collaborative and interdisciplinary environment of a global experiment.

Expectation for candidate. Enthusiasm for understanding the fundamental laws of nature and willingness to learn more about the world of particle physics. Computing skills such as python are helpful but also can be acquired during the project. English working proficiency is required.

Foundational Physics

Luca Marzola (luca.marzola@cern.ch)

Annotation. Everything physical is information-theoretic in origin. This is the essence of the mantra "It from bit" coined by J. A. Wheeler to harp on the idea that quantum mechanics should be grounded in physical principles characterizing our reality rather than in a set of axioms that tells nothing about the world. And what is more fundamental and physical than information? Simply nothing: even the laws of physics do not apply to the objects that we probe in a laboratory, but only to the description of the world — to the information — that we obtain through experiment. In this view, quantum mechanics is the formal structure that describes how – and which – information about the world we can acquire and how our beliefs update as new information is gathered. So far, this paradigm-shifting attitude towards Nature has been resonating only within the gravity and quantum mechanics communities. The proposed line of research intends to extend the approach to the study of high energy processes, by exploring the novel area located at the interface between particle physics and quantum information theory.

Expectation for candidate. Interest in particle physics, quantum information theory and quantum computing. Basic understanding of quantum mechanics and particle physics phenomenology, proficiency with mathematical methods for physics and basic computing skills (Wolfram Language, python and Julia). The working language is English.

Rekonstruktsioonialgoritmid LHC heledusfaasi jaoks / Reconstruction algorithms for the high-luminosity LHC

Joosep Pata (joosep.pata@cern.ch)

Teema tutvustus. CMS eksperiment CERNis on ehitatud mõõtma kõrge energiaga prooton-prooton põrgetes tekkivaid osakesi. Eksperimenti eesmärgiks on muuhulgas täpselt mõõta Higgsi bosoni omadusi ning avastada potentsiaalseid uusi kõrge energia interaktsioone ja osakesi. Järgnevatel aastatel läbib detektor uuenduskuuri, mille käigus suurendatakse detektori osade lahutusvõimet ning ka põrgete hulka ajaühikus, st. andmete hulk ja keerukus suureneb drastiliselt. Seetõttu on vaja välja arendada uued rekonstruktsioonialgoritmid, mis oskavad signaale täpselt rekonstrueerida püsides arvutusliku võimekuse piires. Üks paljulubav suund on nn. heterogeenne arvutus (GPUd, FPGA-d), kus algoritmides on vaja kasutada paralleliseerimist. Konkreetset arendame me välja masinõppel põhinevaid rekonstruktsioonialgoritme, mis annaksid täpsema füüsikalise mõõtmise tulemuse, oleksid arvutuslikult efektiivsed ning mida saaks konstrueerida otse andmete põhjal.

Nõuded kandidaadile. Huvi osakestefüüsika ja suuremahulise andmeanalüüsi arvutusliku poole vastu. Soov ja valmidus õppida eksperimentaalse osakestefüüsika põhialuseid, samuti ka arvutiteaduse ja -tehnikat printsiipe. Konkreetset kasutame Pythonit andmeanalüüsiks, juhitud masinõpet (tensorflow, pytorch), kirjutame GPU algoritme C++-is. Me jooksutame arvutuslikke eksperimente, parendame olemasolevaid algoritme, interpreteerime tulemusi, koostame inglisekeelseid raporteid ja ettekandeid CERNi kaastöölisele.

Annotation. The CMS experiment is a general-purpose high energy particle detector located at CERN. The goals of the experiment range from measuring the properties of the Higgs boson to discovering new fundamental particles and interactions. In the upcoming years, the detector will undergo upgrades which increase the data rate and detector granularity. To address the computational challenges that the new high-luminosity phase brings, new algorithms must be developed that make use of heterogeneous computing (GPUs, FPGAs) to be able to efficiently reconstruct the collision events. In particular, among other topics, we investigate machine learning methods to develop reconstruction algorithms that increase the physics potential of the experiment, are computationally efficient and driven by data.

Expectation for candidate. Interest in particle physics and in particular, the computational aspects of large-scale data analysis in a collider experiment. We expect a willingness to learn introductory particle physics concepts, basic computer science & computer engineering. Specifically, we use Python for data analysis, supervised machine learning methods (we use tensorflow, pytorch), GPU/CUDA software development with C++. We will be interpreting results from computer experiments, developing improvements to the existing algorithms, preparing reports and presentations in English for collaborators at CERN and around the world.

Osakestefüüsika fenomenoloogia / Particle physics phenomenology

Martti Raidal (martti.raidal@cern.ch)

Teema tutvustus. Osakestefüüsika fenomenoloogia on teadusala, mis jääb eksperimentaalse ja teoreetilise osakestefüüsika vahele. Peamine tegevusvaldkond on matemaatiliste mudelite loomine ja nende kontrollimine eksperimentitulemuste abil. Meie uurimisrühm keskendub uusimatele eksperimentaalsetele tulemustele kiirendi- ja astrofüüsikast, tumeaine detektoritest ja

kosmoloogilistest eksperimentidest. Meie töörühm on rahvusvaheline ja töökeeleks on inglise keel, <https://hep.kbfi.ee/>.

Nõuded kandidaadile. Huvi osakestefüüsika vastu, matemaatilised teadmised (diferentsiaalvõrrandid, kasuks tulevad teadmised ka väljateooriast), võime iseseisvalt õppida ja koostööd teha.

Annotation. Particle physics phenomenology is the field of study between experimental and theoretical particle physics. The main activity is mathematical model building and testing the models against experimental hints of new physical phenomena. Our research group is focused on most up-to-date experimental results from accelerator physics, astrophysics, direct detection and cosmological experiments. Our research group is international and the working language is English, <https://hep.kbfi.ee/>.

Expectation for candidate. Interest in particle physics, skills in mathematics (differential equations, possibly field theory), strong self-learning and collaborative working abilities.

TMR (NMR) spektroskoopia tundlikkuse tõstmine / Enhancing the sensitivity of NMR spectroscopy
Indrek Reile (indrek.reile@kbfi.ee)

Teema tutvustus. Magnetresonantsil põhinevad tehnoloogiad (MRT/MRI ja TMR/NMR) on asendamatuks analüüsitehnikateks paljudes valdkondades meditsiinist fundamentaalteaduseni. Magnetresonantstehnikate tugevusteks on nende analüütiline robustsus, universaalsus ning mitte-destruktiivsus (analüüsivat ei kahjustata). See-eest piirab magnetresonantstehnikate kasutusvaldkondi meetodi peamine nõrkus – madal tundlikkus. Tomograafias (MRT) põhjustab madal tundlikkus pikkasid analüüsiaegasid. Spektroskoopias ja analüütilises keemias (TMR) põhjustab madal tundlikkus kõrget detekteerimisbarjääri. Tundlikkus on üks peamisi põhjuseid, mis TMR ei ole paljudest olulistest analüüsivaldkondades konkurentsivõimeline: haiguste biomarkerite uuringud, ravimite metabolismi uuringud jne.

Meie uurimistöö keskendub TMR spektroskoopia tundlikkuse tõstmisele. Peamiseks eesmärgiks on tõsta tundlikkust piisavalt, võimaldamaks TMR rakendamist uutes valdkondades ja seeläbi muuta magnetresonantstehnikad kiiremaks ning populaarsemaks. Projektiga liituvad tudengid osalevad TMR signaali võimendamise meetodite arendamises ning uute rakenduste välja töötamises. Esmajärjekorras keskendume biokeemia ja -meditsiini rakenduste arendamisele, kus TMR on seni olnud tundlikkuse tõttu välistatud.

Nõuded kandidaadile. Projektiga liituv tudeng omandab vajalikud tehnilised oskused biokeemias ja TMR spektroskoopias. Töö keskseks teemaks on spektroskoopia rakendamine ja TMR füüsikaliste aluste omandamine, kuid kandidaat puutub kokku ka biokeemia ja biofüüsikaga. Projekt annab hea põhja edasiseks karjääriks TMR spektroskoopias, biokeemias või biofüüsikas. Peamiseks nõudmiseks kandidaadile on valmisolek osaleda interdistsiplinaarses uurimustöös kus on vaja omandada teadmised nii spektroskoopias kui biokeemias. Varasem kokkupuude TMR spektroskoopiaga oleks plussiks, kuid ei ole hädavajalik.

Annotation. Magnetic resonance techniques (MRI, NMR) are particularly valuable analytical techniques in various fields, ranging from medicine to fundamental science. They are renowned for being robust, indiscriminative and non-destructive. The wider application of these techniques is, however, held back by their main drawback - their insensitivity. In MRI, insensitivity causes long analysis times. In analytical chemistry, insensitivity causes a high limit of detection. Sensitivity is often low enough to exclude NMR from several valuable applications, such as disease biomarker research, drug metabolism studies, etc.

Our research addresses the sensitivity of NMR. The aim is to raise sensitivity sufficiently to allow adoption of NMR in new application fields that are, at present, left to other analytical techniques. Interested students will be involved in developing NMR signal enhancement techniques and developing new applications for NMR. We will prioritize development of biochemical and biomedical applications, where NMR has traditionally been unsuccessful due to the low sensitivity.

Expectation for candidate. The student will learn the necessary skills in NMR spectroscopy and in biochemistry. The central theme will be applied NMR and the student will learn the essential physical and quantum mechanical principles of NMR, but will also be exposed to biochemical and biomedical research. Hence, the candidate can develop skills in several areas. The project will lead to a strong basis for a future career in NMR spectroscopy, biochemical research or biomedical research. The main expectation is willingness to engage in interdisciplinary research wherein the candidate is expected to develop his/her skills in NMR spectroscopy and in biochemistry. Prior knowledge of NMR spectroscopy will be a plus, but not a necessity.

Materjalide THz spektroskoopia / THz spectroscopy of materials

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Teema tutvustus. THz spektroskoopia on uus kiirelt arenev spektroskoopia valdkond, mis jääb mikrolaine ja infrapuna spektroskoopia vahelisse sagedusalasse. Näiteks saab selle tehnikaga mõõta molekulide pöörlemise ja aatomite ning magnetmomentide võnkumise sagedusi. Tööd on võimalik teha madalatel (4K) ja väga madalatel (<1K) temperatuuridel tugevates magnetväljades ning samuti toatemperatuuril töötavate THz spektromeetritega.

Nõuded kandidaadile. Huvi kvantnähtuste vastu.

Annotation. THz spectroscopy is a rapidly evolving spectroscopy where the frequency range is between microwave and infrared spectroscopy. This technique, for example, measures rotation frequencies of molecules and vibration frequencies of atoms and magnetic moments. Spectrometers operating at low temperature (4K) and below 1K in high magnetic fields and at room temperature are available.

Expectation for candidate. Interest in quantum phenomena.

Mittelineaarne optika ja mitmefootoniline spektroskoopia / Nonlinear optics and multiphoton spectroscopy

Charles Stark (charstark@gmail.com)

Aleks Rebane (aleks.rebane@kbfi.ee)

Teema tutvustus. Mittelineaarsed optilised nähtused on fotofüüsikalised protsessid, mis käivituvad intensiivse elektromagnetkiirguse, näiteks suure võimsusega laseri toimetel. Võimsusest sõltuvus võib viia fokuseeritud efektideni, mida saab kasutada 3D-printimises ja 3D-mikroskoopias, kuid molekuli ja kahe või enama footoni vahelised fundamentaalsed interaktsioonid võivad pakkuda palju rohkem rakendusvõimalusi, mis alles vajavad lahtimõtestamist.

Nõuded kandidaadile. Huvi füüsika/keemia, optika ja spektroskoopia, femtosekundlaserite, kvantmehaanika ja molekulaarsümmeetria, lineaaralgebra/maatriksarvutuste vastu.

Annotation. Nonlinear optical phenomena are photophysical processes that emerge in the presence of intense electromagnetic radiation, such as from a high-power laser. The dependence on power can lead to focused effects, with applications in 3D-printing and 3D-microscopy, but fundamental interactions between a molecule and two or more photons may provide many more tools yet to be understood.

Expectation for candidate. Interest in physics/chemistry, optics and spectroscopy, femtosecond lasers, quantum mechanics and molecular symmetry, linear algebra/matrix calculations.

Magnetomeetria rakendused kvantoksiidides / Magnetometry of quantum oxides

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Teema tutvustus. Mitmesuguste pulbriliste, kristalsete ja õhukeste kilede kujul magnetiliste kvantoksiidide omaduste uurimine temperatuurivahemikus 2 – 400 K ja magnetväljades tugevusega kuni 14 T. Magnetomeetria lisaks on soovi korral võimalik omandada algtõdesid nii tuuma- kui kvadrupolresonantsi ning aatom- ja magnetjõumikroskoopia tehnikatest.

Nõuded kandidaadile. Huvi eksperimentaalfüüsika vastu, TTÜ füüsikakursuste edukas läbimine, käelise tegevuse soodumus, hoolikkus ja püsivus, algteadmised programmeerimisest (LabView, Python) ja andmetöötlustest (Python, Origin).

Annotation. We investigate magnetic properties of various quantum oxides in form of a polycrystalline powder, single crystal, or thin film in temperature range of 2 – 400 K and under applied magnetic field up to 14 T. Next to bulk magnetometry it is possible to gain insight also into nuclear magnetic or quadrupole resonance (NMR/NQR) techniques and/or atomic and magnetic force microscopy (AFM-MFM).

Expectation for candidate. Interest for materials research and experimental condensed matter physics, successful passing in physics courses offered by TUT, careful and stable character, some programming (LabView, Python) and data analysis (Python, Origin) experience.