Understanding the Early Universe: interplay of theory and collider experiments

THE PROPOSAL DESCRIPTION

1 Current knowledge in the field and preliminary work

This is a collaboration project between the particle and cosmology theory group at the Faculty of Physics, University of Warsaw and the experimental group at the Department of Physics and Technology, University of Bergen. The project is devoted to fundamental research with the goal of contributing to the ultimate construction of a deeper than the Standard Model theory of the elementary interactions that would help to understand the history of the Early Universe.

1.1 The state of knowledge

There are two well known and highly publicized points about the present state-of-the-art in the physics of elementary interactions. One is the great success of the Standard Model (SM) [1], completed by the discovery of the Higgs-like particle. The SM also explains the cosmological history of the Universe, starting with the phase transition in strong interaction (chiral symmetry breaking) few parts in a million of a second after the Big Bang, confirmed by many astrophysical experiments [2]. The other point is that, nevertheless, the Standard Model leaves several fundamental puzzles unexplained, within itself and in the history of the very Early Universe [2]. Those puzzles have been for long time the guiding principle for enormous theoretical and experimental activity in search for beyond the Standard Model theory.

On the SM side, the present understanding is plagued with several issues such as the hierarchy problem in the Brout-Englert-Higgs mechanism, the strong CP problem, lack of the theory of flavour explaining fermion masses and mixing, to give few examples [3]. On the cosmological side, the SM fails to explain the existence of Dark Matter and matter-antimatter asymmetry in the Universe.

It is tempting to expect that unexplained observational puzzles in cosmology are linked to those of the Standard Model itself and both will find explanation in a framework of the same deeper theoretical structure. One example is the WIMP (Weakly Interacting Massive Particle) paradigm [2]. It has been known that if the Dark Matter is a weakly interacting particle with mass around TeV scale, the observed energy density can be explained by the thermal freeze-out mechanism. This is particularly interesting because many solutions to the hierarchy problem necessarily introduce weakly interacting particles around TeV scale.

The origin of matter-antimatter asymmetry (baryogenesis) may also be related to the Beyond the Standard Model (BSM) physics **around the TeV scale**. Its explanation requires beyond the SM sources of the combination of the Charge parity and Parity (CP) symmetry violation [4, 5]. Baryogenesis at the electroweak phase transition (EWPT) would in addition require this transition to be a strong enough 1st order phase transition (it is 2nd order in the SM)[1]. In general, BSM models introduce some modification to the electroweak (EW) potential, changing the strength of the EWPT and have more freedom to accommodate new sources of CP violation. The existence of new symmetries (e.g. supersymmetry), extra dimensions or hidden sectors, new interactions and new particles would shed light on the puzzling aspects of the SM.

As mentioned above, the two main cosmological problems (Dark Matter and matter anti-matter asymmetry) may well be linked to the BSM physics around the TeV scale. The most important "experimental tool" to probe the TeV physics are the general purpose laboratories at the Large Hadron Collider (LHC): ATLAS and CMS. These experimental collaborations are in the process of the full analysis of the Run 2 data, corresponding to around 160 event/femtobarn and are busy preparing the

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[1] The well known three conditions for baryogenesis have been formulated by Sakharov [6]: baryon number violation, C-symmetry and CP-symmetry violation, interactions out of thermal equilibrium. For electroweak baryogenesis, the Sakharov conditions have to be satisfied at the temperature close to the EWPT and this requires a strong enough 1st order phase transition.

analyses for High Luminosity LHC (HL-LHC) where amount of data ranging to 3000 event/femtobarn per experiment are expected. **The aim of our proposed project is to investigate the two main cosmological issues by means of the most powerful collider experiments (HL-LHC) and High Energy LHC (HE-LHC) through a close collaboration between the theory and experimental teams.**

Measurements performed so far in the Standard Model and Higgs sector, top and b-quark sector are based on full or partial Run 2 data set. **Several recent results are pertinent to this proposal:**

- Higgs Yukawa couplings have been measured with accuracy of 10% and are so far in agreement with the SM [7, 8], 5 sigma observation of the $pp \to ht\bar{t}$ production was registered for the first time [9, 10].
- An attempt to measure CP-state of SM Higgs-like particle in $\tau\tau$ final states was performed. ATLAS has measured [11] an admixture of CP-odd matrix element to be $\bar{d} \in [-0.090, 0.035]$ at 68% confidence level, for VBF produced Higgs-bosons decaying to $\tau\tau$.
- Limits on the Higgs-self coupling (triple Higgs coupling) have been set (see e.g. [12]), however HL-LHC is needed to reach the sensitivity to the SM value.
- Wide range of searches for New Particles has been performed. Searches for WIMPs have been performed from a wide angle of approaches, with negative results. The results of searches motivated by supersymmetry (SUSY) or other more exotic beyond SM models are also negative.

Currently, direct BSM searches conducted by ATLAS and CMS collaborations at the LHC have been based on two different and complementary strategies. One is called "simplified model" approach [13], which assumes a simple production process for a (pair of) new heavy particle(s) followed by a concrete decay mode. This approach tends to oversimplify the real signature, which is usually a mixture of many different productions and decay modes. The other approach is testing concrete models one by one by scanning its parameter space. One of the drawbacks of this approach is that one has to pick up a particular model out of zoo of new physics scenarios, so the result has only limited implication to the BSM scenarios as a whole. Also, the theory parameter space is often too large, requiring unaffordable amount of computational resources. For example, the study presented in [14] targeted a supersymmetric model with 19 parameters, while only $\sim 10^6$ points are tested. This sample size is too small compared to the volume of the 19-dimensional parameter space, which makes it very difficult to draw any firm conclusion on this model. In order to obtain the general picture of possible BSM scenarios, a truly (or more) model-independent studies on new particles are necessary, although such a study is, in general, difficult to be carried out at hadron colliders.

As mentioned above, EW baryogenesis (EWBG) is an attractive scenario that is testable at the HL(HE) LHC. There are several studies linking this scenario with the collider signatures (see e.g. [15, 16]). Most of those studies have investigated particular models that give a strong 1st order phase-transition and studied the signature in the di-Higgs production channel. However, their conclusion strongly depends on their model assumptions, and general link between the 1st order phase-transition and its collider reach has not been established. Also, the ultimate sensitivity of the di-Higgs channel at the HL(HE) LHC is still not clear, which is very important to understand the future collider implication to the EW baryogenesis.

Another important condition of the EW baryogenesis is new sources of CP violation. The collider implication to this condition is much less studied compared to the phase-transition requirement. Only recently, phenomenological studies by theorists have been carried out on the CP-phase measurement for the t-t-h and τ-τ-h couplings at the LHC [17, 18], but those studies need to be extended by including various important effects such as pile-up and detector resolutions that are missing in the previous studies. Also, it is unclear whether the HL(HE) LHC can probe the minimal amount of CP violation required by the EW baryogenesis, which must be answered by a joint theoretical and experimental research, to understand the testability of EW baryogenesis at colliders.

The last but not least condition for baryogenesis is baryon number violation. In the EWBG, this requirement is satisfied by the non-perturbative sphaleron process [19] at high temperature. Interestingly, several theoretical studies suggest that the sphaleron process may be observable in the collider environment [20, 21, 22]. However, these estimates suffer from large theoretical uncertainties, and the collider search for sphalerons is very important since it will provide an important experimental constraint in understanding the validity of theory calculations. Recently, CMS have performed the sphaleron search analysis and derived a first collider limit on this process [23]. However, the CMS have missed important multi-W effects [24], which would dramatically alter the nature of sphaleron events. A proper simulation of sphaleron events and the collider study to discriminate sphelron events from other similar signatures are timely and urgent tasks to be carried out.

Thus, we are still far away from the full exploration of the TeV scale in search for BSM physics.

1.2 Novelty, originality and degree of innovation

We would like to stress three-fold novelty and originality of our proposal:

Novelty in the choice of the research objectives:

Guided by the questions relevant for the very early history of the Universe, we focus on the exploration of few experimental signatures that are generic for **a broad spectrum of new physics models and, in fact, even for new phenomena with no concrete theoretical frameworks proposed yet.** Our goal is to draw, as far as possible, model independent conclusions on the BSM phenomena.

Novelty in physics program:

In the proposed project, a number of important questions motivated by the issues in the early Universe will be addressed with the HL(HE) LHC experiments in mind, which will be the most powerful and adequate tool to probe the physics at the TeV scale.

When tackling the puzzles of Dark Matter, we will propose a truly model-independent study on new particles at the LHC, which will provide a useful and general constraint on any type of Dark Matter models that are accessible to the HL(HE) LHC. Establishing such a model-independent constraint is very rare in hadron colliders.

Regarding the EW baryogenesis, we shall be asking and answering critical questions, such as "What is the minimal signature in the di-Higgs channel when asking the BSM scenarios for a strongly 1st order phase-transition?", "What is the ultimate sensitivity for the di-Higgs measurement achievable at the HL(HE) LHC?". The studies constructed from this direction are new and will bring useful and definitive information about the testability of EW baryogenesis at the HL(HE) LHC.

On top of this, we shall be studying the testability of baryon number violation relevant to the EW baryogenesis, i.e. the sphaleron process, at the HL(HE) LHC. Such a study is very rare since the process is purely non-perturbative. We shall be going one step further and compare the sphaleron events with resembling mini black hole events [25] and establish the methodology of distinguishing them. The study in this direction has never been carried out before but will be important if sphaleron-like signatures are observed at the HL(HE) LHC.

Novelty in methodology:

This project is based on a close collaboration between the experimental and theoretical groups, with joint research in all tasks. From the experimental side, we shall propose improved methods of the data analysis and of their presentation, suitable for the corresponding theoretical investigations. Machine Learning techniques will be broadly used. One of the most recent developments in the LHC data analysis is exploitation of the Machine Learning algorithm. This method is proven to be very powerful in the measurement of Standard Model processes (see e.g. [26]), but its application to direct BSM searches is so far less explored (see however [27, 28]).

On the theory side, we shall critically review the existing theories and investigate several new ones. Our theoretical goal is to draw a big theoretical picture on the BSM physics that will emerge after the HL-LHC and HE-LHC data analyzed with the signatures addressed in this project.

Once our results will be used in the actual data analysis, either new discoveries and their theoretical interpretation will come or new constraints on theoretical ideas will be obtained, depending on what the nature offers us. The feasibility of the proposed research is guaranteed by the very high expertise of both teams and by their continued involvement in the current research. A detailed discussion of the feasibility of the research objectives will be presented in sec. 2 and 3 of this description, once concrete objectives and the plan of the work are discussed.

2 Objectives

In this project we shall pursue a number of concrete novel approaches and tasks, that in our opinion should bring us (as the whole research community) closer to the ultimate goal of finding the extension of the SM that will explain the puzzles of the early universe. **The guiding principle for our choice of the objectives is the existing observational puzzles that SM is not able to explain**, that is existence of Dark Matter, the need for additional source of CP violation to explain the observed matter-anti matter asymmetry and, considering the EW baryogenesis to be an interesting option, the characteristic of the EW phase transition.

Our identification of New Physics signatures of interest which structure our research programme in its experimental and theoretical aspects is **A) Monojet signature, B) Mono-Higgs signature, C) Di-Higgs production, CP state of $pp \to t\bar{t}h$ and $h \to \tau^+\tau^-$, D) Multi-jet signatures.**

The objectives of this proposal are:

1. **Machine learning assisted mono-jet analysis in search for dark matter and new electrically neutral stable particles and its theoretical interpretation.**
2. **Discriminating theories by joint mono-jet and mono-Higgs analysis.**
3. **Constraining the mechanism of the Electroweak Phase Transition by di-Higgs boson production, $pp \to hh$.**
4. **Probing new sources of CP violation in the Higgs-fermion sector.**
5. **Investigating the sphaleron and mini-black hole production at the LHC and its dependence on the mechanism of the EWPT.**

In each case we shall:

- Develop best strategies for reaching those objectives in the experiments at the upgraded LHC aided by an investigation of new data analysis techniques;
- Estimate the chances for the observation of the corresponding signatures in the realistic experimental environment at HL(HE)-LHC, based on the guiding by a broad spectrum of the existing and new theoretical models;
- Analyze the existing and new theoretical models from a new angle of documenting the similarities and differences in their experimental signatures;
- Study the theoretical interpretation of the potential new discoveries.

These objectives can only be realized in a close collaboration between experimentalists and theorists.

AD 1

The mono-jet signature is a class of events where there are energetic jets on one side of the detector and a large missing transverse energy (MET) on the opposite side. It signals a direct production of neutral collider-stable particle(s) χ (i.e. $pp \to \chi\chi +$jets) or their indirect production via charged or coloured particles η, e.g. $pp \to \eta\eta +$jets followed by $\eta \to \chi + X$, where X is soft objects not to be reconstructed due to detector resolution. For X to be soft, we assume η and χ are almost mass degenerate, which will be justified later due to the co-annihilation mechanism of Dark Matter freeze-out. The energetic jets in this signature originate from a high transverse momentum gluon or quark coming from initial state radiation (ISR).

Among many BSM search channels, the mono-jet signature is special because it does not exploit the decay products of the new particles; what is observed is only ISR jets and the signature is, therefore, independent of the decay of η, provided it is detector-size long-lived. This feature enables us to design a model-independent interpretation of the mono-jet search in terms of such charged particles η. For example, let us define the particle η in terms of its spin and (non-singlet) representation under the SM gauge group. This information is already enough for us to calculate the conservative limit on its production cross section (via gauge interaction)[2] and simulate the production of $pp \to \eta\eta +$ jets as a function of the mass of η. Thus, by comparing the mono-jet data and the theoretical prediction, one can compute the projected mass reach for η for various collider options. **In this part of the project, we shall perform a Monte Carlo simulation for production of new particles (defined by its spin and gauge symmetry representation) and create an encyclopedia of projected mass reach for various types of new particle for several collider options.** The scientific value of this research is very high because this result is genuinely model-independent (since its depends only on the spin and charge of the particle) and will be useful for many years. Once the result is published, one can always find the particle in question in the list of our result and immediately tell the necessary collider energy and luminosity to discover/exclude that particle.

The result of this study will have a wide rage of application. For example, in the co-annihilating dark matter scenario, there is a quasi-mass-degenerate particle, η, together with the dark matter particle, χ, in the spectrum. Our result will directly be applicable to such a scenario. The result can also be applied to the production of charged long-lived particles decaying outside the detectors into actual dark matter particles, due to a very weak coupling, whose relic abundance would be determined by the freeze-in mechanism (for a recent study, see e.g. [29]). Also, the invisible particle χ in our analysis may not constitute fully the observed dark matter density. There are many such interesting theories; for instance, a large parameter region of the Minimal Supersymmetric Standard Model [30] has such an underabundant neutralino. The main component of dark matter could then be, for example, axions.

After completing the model-independent study, we are going to extend our study to a mildly-model-dependent area, where the neutral collider-stable particles are directly produced in monojet events, due to the U(1) kinetic mixing or to the energy-momentum tensor; here belongs e.g. radion production, gravitational KK modes production, hidden sector dark matter production. The mono-jet signature can give interesting information about such theories, although the results would depend on one or two free parameters. In some of these models additional signatures arise, for example mono-Higgs, that we plan as well to explore. The monojet searches for new electrically neutral particles, produced either as decay product of a charged one or directly, are insensitive to their possible coupling to the Higgs boson. Such coupling would be constrained e.g. by direct dark matter detection experiments, such as LUX, PandaX and LZ, which will provide additional constraints in concrete models.

Within this project, we shall not only work on interpretations of the mono-jet result but also develop a powerful mono-jet analysis by using Machine Learning (ML) technique. The main idea is to exploit the ML algorithm to discriminate the radiation pattern of the ISR in the signal events $pp \to \eta\eta +$ jets from that in the main background process $pp \to Z +$ jets followed by $Z \to \nu\bar{\nu}$. The details of our ML-assisted analysis will be described in detail in sec. 3.

In summary, in this part of the project we intend to establish a model-independent framework of interpreting the mono-jet results. We also propose and study a novel method of controlling the main background in the mono-jet channel by means of the Machine Learning technique.

AD 2

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[2] This estimation is conservative, because the cross-section can be made larger if one assumes additional interactions between η and SM particles other than the gauge interaction.

The mono-Higgs signature is characterized by final states consisting of the Higgs boson and missing transverse momentum, possibly due to experimentally undetectable particles. This signature was exploited so far to search for Dark Matter candidate particles produced along with the Higgs boson. The production mechanism depends on a class of models in which there exists a coupling between the Higgs boson and a mediator of DM-SM interactions and/or coupling between the Higgs boson and Dark Matter.

Bergen group is presently responsible for the ATLAS search of the mono-Higgs signature with $h \to \tau^+\tau^-$. Compared to searching for mono-Higgs in a more abundant $h \to b\bar{b}$ final state the τ signature can be better separated from multi-jet background allowing a relaxed missing transverse energy requirement and an increased sensitivity to lower masses of Dark Matter particles. The present scope of the analysis is the ATLAS Run II legacy paper. This engagement can be extended and exploited in a novel way in the framework of this project, thanks to the collaboration with the theory group. We shall propose novel data analysis approaches to increase the sensitivity to mono-Higgs signature with taus. The sensitivity of the HL(HE)-LHC to this signature will be estimated and the discrimination power for theoretical models of joint mono-jet and mono-Higgs analyses will be investigated.

AD 3

For the electroweak baryogenesis, the Sakharov's conditions have to be satisfied at the temperature close to the electroweak phase transition (EWPT) and this requires a strong enough 1st order phase transition [31]. However, the SM with the actual values of its parameters does not have enough of CP violation [4, 5] and, with the temperature effects included, the phase transition is only 2nd order. So, EWBG requires some extension of the SM. A 1st order phase transition at the EW scale can occur in two ways. One way is a single field phase transition when only the Higgs field gets a vacuum expectation value (vev) at high temperature and the transition is 1st order due to a modified Higgs effective potential. Another way is a multi-field phase transition with at least one more, in addition to the Higgs, scalar field getting a temperature dependent vev. This case can be further split into two options: the additional field is electroweakly charged or is a singlet of the SM group and the actual dynamics of the phase transition depends on this choice. In all cases one needs new degrees of freedom, playing different roles as a function of the temperature, that would also modify the Higgs potential at zero temperature. In particular, those strongly 1st order EWPT models often predict modification in the triple Higgs coupling, $\mathcal{L} \ni c_3 hhh$, which can be measurable in the di-Higgs production channel at the HL(HE) LHC.

The measurement of di-Higgs process is very important to constrain the EWBG models but its production rate in the SM is very small and the expected sensitivity at the HL LHC is not impressive [32]. It is not obvious how well the EWBG models can be constrained by the HL(HE) LHC quantitatively. **In our proposed project we tackle this question from both theoretical and experimental directions. The theory team is going to determine the minimal deviation in the triple Higgs coupling required by the strong 1st order EWPT in the classified above scenarios, while the experimental team will investigate the absolute sensitivity to the triple Higgs coupling that can be achieved at the HL(HE) LHC, introducing a number of new improvements to the traditional analysis.**

AD 4

Successful EWBG requires CP violating interaction between the particles in the thermal plasma and the bubble wall separating the symmetric and broken phases. Since the bubble wall is nothing but a spatially varying Higgs field, this implies the CP violation is expected in the Higgs-fermion sector. The LHC is a unique machine that can produce the Higgs particle, and the direct measurement of the Higgs-fermion interaction is possible. The most promising channels are the $pp \to h \to \tau^+\tau^-$ for the h-τ-τ coupling and the $pp \to ht\bar{t}$ process for the h-t-t coupling. The effect of the CP-phases to these processes can be studied in the framework of effective field theories [33].

The information of the CP phase in the h-τ-τ coupling is present in the correlation between the decays of two taus originated from $h \to \tau^+\tau^-$. Recently, a variable maximally sensitive to the CP phase in the $h \to \tau^+\tau^-$ process has been proposed in the events with two taus decaying as $\tau \to \pi^0\pi^-$ [18]. However, calculation of this variable requires reconstruction of two unknown neutrino momenta, which brings a large uncertainty in the CP phase measurement. Also, the background coming from $Z \to \tau^+\tau^-$ contaminates the event sample and deteriorates the sensitivity even further. In Ref. [34], our experimental team members proposed a novel technique for the Higgs mass reconstruction in the $h \to \tau^+\tau^-$ channel, where the neutrino momenta are partially reconstructed. This technique can be used to improve the calculation of CP sensitive variables as well as reducing the $Z \to \tau^+\tau^-$ background, separating the Z mass from the Higgs.

It has been known that the CP phase of the h-t-t coupling can be measured by inspecting the correlation between the two top decays in the $pp \to ht\bar{t}$ process. One of the pioneering works has been done by one of our theory team members [35]. While this study proposed the concept of CP measurement and various CP sensitive variables, feasibility studies based on Monte Carlo (MC) simulation have not been performed until recently. In Ref. [17], a first MC-based study has been presented. In their analysis, however, important detector effects have been neglected and the CP-sensitive variable was not optimized.

It has been known that the CP violation in the Higgs-fermion sector is strongly constrained by the electron EDM, since h-f-f coupling enters the EDM diagrams at 2-loop. However, one has to keep in mind that this constraint is indirect in a sense that any other new physics contribution can cancel this effect in the loop. Therefore, the direct probe of CP nature of the Higgs-fermion interaction at the collider is very important.

It is now the right time to study the CP measurement of $h \to \tau\tau$ and h-t-t couplings via $h \to \tau\tau$ and $pp \to htt$ processes. In this proposed project, measurements of these processes will be investigated with a number of improvements. We shall determine the ultimate sensitivity achievable at the HL(HE) LHC and confront it with successful models of EWBG.

AD 5

The baryon number violating interaction is one of the important requirements of baryogenesis. In the EWBG, this condition is satisfied by the so-called sphaleron process, which is non-perturbative quantum process changing the topological number of the non-trivial Higgs and EW field configurations. At a high-temperature ($T \gtrsim 100$ GeV), this process is active, while at the zero-temperature zero-energy limit, this process is exponentially suppressed.

Historically, the question whether the high-energy collider can produce sphalerons has attracted attention, and several calculations have suggested that the sphaleron production rate at HL(HE) LHC may be observably large if the multiple W-boson final states are taken into account [20, 21, 22]. If sphaleron processes are observed at the HL(HE) LHC, the implication is significant, since this process is indispensable for baryogenesis and it in principle tells us the global shape of the Higgs-EW potential away from the trivial perturbative vacuum. Even though the current theoretical understanding for the high-energy sphaleron process is premature, the experimental search is important since it can derive experimental constraints, which will help to guide theoretical works to understand this non-perturbative process.

Pioneering works of the collider phenomenology of sphalerons has been performed by one of our theory team members [36, 24]. Following this work, CMS experiments went on to look for this process and derived a first collider constraint [23]. However, the MC simulation performed by the CMS entirely ignored the multi-W productions, which is a crucial ingredient to make the sphaleron production rate observably large. Very recently, one of our team members have implemented sphaleron processes in `Herwig-7` event generator [37] (a computer program commonly used by ATLAS and CMS for event simulation) properly taking the multi-W effects into account. The machinery is finally ready for realistic collider simulations for sphaleron processes.

If sphalerons are produced at a collider, the event will be spectacular; the final state contains $\mathcal{O}(30)$ W-bosons plus 7 anti-quarks and 3 anti-leptons (some of them may be neutrinos). Since W-bosons decays into the SM fermions, at the detector level, the final state is seen as the events with $\mathcal{O}(50)$ jets plus multiple leptons with some missing transverse energy (from neutrinos).

Multi-jet signatures are characteristic for a wide class of beyond SM models. Two of them will benchmark our studies, sphaleron and microscopic black hole productions. While the signature is similar, their physical origin is very different. Unlike sphalerons, microscopic black holes with observably large production rate arise in models with relatively large extra spatial dimensions, in which gravity is as strong as other forces at the scale of these extra-dimensions [38, 39, 40, 41]. A microscopic black hole, in "classical regime" will most probably "evaporate" nearly instantly producing various SM particles according to the thermal black body distribution (known as Hawking radiation). These characteristics can help distinguish sphalerons from black holes and from the multi-jet QCD processes.

The question whether the sphaleron events are distinguishable from the black hole events at the LHC is non-trivial and important one, and in the proposed project we will tackle this question by developing ML-aided methods. We will estimate the chances to observe and distinguish sphalerons from black holes based on the large class of existing and new models of both effects. We will analyse which information on the Higgs potential and bariogenesis one can get from limits/observation of sphaleron induced processes at HL(HE) LHC.

3 Work Programme

Our work programme is organized by our objectives described in sec. 2. Our broad tasks are in one to one correspondence with the objectives and they are usually split into several subtasks. Several team members (7-9) from both groups will be assigned to each general task, with two coordinators for each task, one from Bergen and one from Warsaw, who will jointly organize, monitor and participate with the rest of the task team in research.

3.1 Work Programme including proposed research methods

Task 1: Machine Learning assisted monojet analysis in search for new electrically neutral stable particles (1-24th month)

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Coordinators: Kazuki Sakurai, Bertrand Martin Dit Latour

1-1. *Developing a Machine Learning (ML) algorithm to distinguish between hadronic QCD radiation emerging in the SM background processes and new particle production processes.*

We propose a novel, ML assisted approach to use the jet characteristics. The characteristics of the initial state radiation (ISR) jet will depend on the mass scale of the hard interaction. Jets in the background processes will be recoiling against Z or W, while in the signal they could be recoiling against much he. Therefore, the ISR jets in the signal events would, in general, be wider and constituted by a larger number of hadrons. Experimentally, jets are complicated objects resulting from clustering of energy deposits in calorimeters and reconstructed tracks of charged particles, with a several clustering algorithms and pre-clustering stages possible. Pre-clustered objects are required to point to the most-energetic primary vertex of the event, consisting often to up to 60 individual proton-proton collisions (pile-up). If we embark on the use of unclustered tracks and deposits, the problem is similar to medical image recognition. Bergen group has recently embarked on the adapting Convoluted Neural Networks used in this area to particle detection problems. Recognizing virtuality of the jet from unclustered information is an ideal extension of this activity. Another candidate methods are Boosted Decision Trees (BDT), widely used in ATLAS for particle recognition. A variation of this method, Xboost, used by Google in facial recognition is a tool worth testing in this context.

A selection of reliable training samples of signal and background events is of utmost importance for a reliable ML result. It is important to use the real data. In the usual cut-and-count based selection method, the Monte Carlo simulations for the background are fitted to the experimental data in the dedicated control regions, and verified in independent verification regions. Differences between the prediction and the data in the verification regions are used to get a handle on systematic uncertainties. Methods to study systematic uncertainties while using ML methods have not been developed yet. We are in a strong position here to make an important contribution which can be used beyond the present project. We plan to:

- Work with the existing ATLAS Run 2 **data**/simulations, to chose the best ML method and test the hypothesis that the jet virtuality can be probed from the jet structure and content. Compare the high virtuality ISR jets from signal simulation with ISR jets from $t\bar{t}+$ jet processes.
- Retrain the chosen ML method on realistic, non-proprietary simulation of a Run 2 LHC detector and an HL LHC detector.

We shall obtain the improvement of the sensitivity of the ATLAS Run 2 mono-jet search for New Physics summarized in an ATLAS note and improved from conventional mono-jet searches experimental sensitivity in future collider options (HL LHC, HE LHC) for mono-jet production as a function of the invariant mass of the invisible final state.

1-2. *Translating the above information under very mild model assumption into the discovery potential of (or limits on) the production of the invisible final states, as a function of the spins and SM quantum numbers of the final particles of a given mass.*

We consider the pair production of charged or coloured particles η, which decay subsequently into a mass degenerate neutral partner χ together with some soft objects X, $pp \to \eta\eta +$ jets, $\eta \to \chi + X$. Since X is unobservable, this event topology contributes to the mono-jet signal region. The model-independent (gauge interaction) part of this production cross-section is completely determined by specifying the spin and gauge representation of the particle η up to its mass.[3] By comparing the theoretical prediction and the result of ML-aided analysis obtained in **1-1**, we will create an encyclopaedia of projected mass limit and discovery reach from the improved mono-jet analysis on various types of new particles for several collider options, HL LHC and HE LHC. Due to its highly model-independent nature, this information will be useful for many years. It is rare to be able to obtain such a strongly model-independent information at hadron colliders.

1-3. *Studying the impact of mono-jet search on motivated BSM scenarios.*

With the results of **(1-2)**, we shall address motivated BSM scenarios, such as e.g. the co-annihilating dark matter scenario, with η quasi-mass-degenerate with the dark matter particle, χ. The result will also be applied to the production of charged long-lived particles decaying outside the detectors into actual dark matter particles, whose relic abundance would be determined by the freeze-in mechanism. The invisible particle χ in our analysis may not constitute fully the observed dark matter density. They may or may not have possible coupling to the Higgs boson. Such coupling would be constrained e.g. by direct dark matter detection experiments, such as LUX, PandaX and LZ, which will provide additional constraints in concrete models.

In order to make our analysis as general as possible, we also consider the direct production of a gauge singlet particle χ. Here we explore several attractive BSM scenarios in a mildly-model-dependent way. In order to have non-zero production rate, one must assume an interaction between χ and SM particles, introducing additional free parameter; this includes the possibility of the kinetic mixing interaction, mediation via a non-SM particle and coupling to the trace of the energy-momentum tensor. Using the result obtained in **1-1**, we derive the projected limit and reach in the mass vs coupling parameter plane assuming several collider options. We also study how these models are contained by other signatures, such as the mono-Higgs signature and the signature via direct production of the non-SM mediator.

In particular, we consider the hypothetical radion production in Randall-Sundrum (RS) models, with stabilized 5th dimension and for investigating some hidden sector scenarios. The analysis of the prospects for the radion production in different RS models is particularly interesting, as it couples to the trace of the energy-momentum tensor. Thus, its production and decay channels are similar to those of the SM Higgs boson, although with different strength. In addition, the

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[3] The production rate can be made even larger if one assumes additional interactions between η and SM particles other than the gauge interaction. In this sense, the projected limit and discovery reach obtained in this analysis is conservative.

mono-jet signature of the radion production is also sensitive to the presence of any kind of electrically neutral and collider-stable new particle, produced in pairs by the radion decay. The RS theories are very interesting theoretically and also can be relevant for the phase transitions in the early universe. We plan to conduct an extensive theoretical investigation of this issue, imposing the constraints from the estimated sensitivity for mono-jets.

Furthermore, all above investigations will be performed in two versions. In the first one we shall be assuming that the neutral particle is the dominant component produced by freeze out of the observed abundance of dark matter or a "parent" of the dominant component produced by freeze-in. Such a requirement will strongly constrain our theoretical analyses. In the second option, we shall be interested in the theoretical scenarios where the neutral particles contribute very little to the dark matter abundance but their existence would be a confirmation of a theoretical scenario interesting for other reasons.

Task 2: Discriminating theories by joint monojet and mono-Higgs boson analyses. (13-36th month)

Team: Krzysztof Rolbiecki, Post-doc 1, Janusz Rosiek (Warsaw), Trygve Buanes, Anna Lipniacka, Therese Berge Sjursen, Konrad Tywoniuk, Post-doc (Bergen)

Coordinators: Krzysztof Rolbiecki, Therese Berge Sjursen

Since many BSM scenarios give rise to the same mono-jet signature, once the signature was found, the BSM scenarios must be properly distinguished. We study how this goal can be achieved using mono-Higgs signature.

2-1. *Developing improved analysis for mono-Higgs final state with $h \to \tau\tau$ channel and estimate its sensitivity.*

The τ lepton is the only lepton whose helicity state can be measured in a LHC detector, via its decay kinematics in the hadronic final state. Thus the spin and the CP state of the particle decaying to $\tau\tau$ can in principle be measured. There are several ideas available, the one from Bergen group uses ML techniques (Deep Neural Networks). Adding spin and CP sensitivity will increase sensitivity in the search for SM mono-Higgs and will allow searching for non-SM mono-Higgs-like particles, with different CP states. We plan to

- Work with the existing ATLAS Run 2 data/simulations, to chose the best ML method to add tau spin information and CP variables to the mono-Higgs search. Test the sensitivity improvement vs a bench-mark model.
- Adapt the results to a realistic, non-proprietary simulation of an HL LHC experiment and analyse the model reach.

2-2. *Discriminating theories discussed in Task 1.*

The theory team will calculate the cross-sections of mono-Higgs final state for each BSM scenario. Joint analysis of existing Run 2 mono-jet and mono-Higgs results will be performed, obtaining limits on models discussed in Task 1. The results of 2-1 will be used and the model reach at HL(HE)-LHC will be analyzed.

Task 3: Constraining the mechanism of the electroweak phase transition by di-Higgs boson production (13-36th month).

Team: Marek Olechowski, Stefan Pokorski, Zygmunt Lalak, Post-doc 3 (Warsaw), Bjarne Stugu, Anna Lipniacka, Post-doc, PhD student (Bergen)

Coordinators: Marek Olechowski, Anna Lipniacka

Extensions of the SM with 1st order electroweak phase transition generically give some modification of the triple Higgs coupling also at zero temperature. The Higgs pair production cross section depends on triple Higgs coupling. Therefore the actual quantitative precision that can be reached at the HL LHC and the HE LHC for that coupling is of crucial importance, to be compared with theoretical predictions.

3-1. *Categorizing theoretical models of the 1st order phase transition and obtaining their predictions for the triple Higgs coupling.*

Extensions of the SM with the 1st order electroweak phase transition will be categorize according to the single-field and multi-field classification introduced earlier. From the point of view of constraining the electroweak baryogenesis experimentally, the important question is how small (and not how large) the triple Higgs coupling at zero temperature can be in each case. We shall investigate systematically this question in a number of models and also with effective parametrizations of the scalar potentials. In each category we shall review the existing theories and study a number of new once. For a single-field phase transition case we shall investigate the occurrence of the 1st order phase transition in models solving the hierarchy problem where the Higgs boson is a (pseudo) Nambu-Goldstone boson with perturbative and non-perturbative dynamics, such as Twin Higgs models [42], supersymmetric Twin Higgs models [43, 44] with the so-called double protection of the Higgs potential [45] and minimal composite Higgs models [46]. Each of them offers new degrees of freedom, which do not acquire any temperature dependent vacuum expectation value (vev) but can modify the temperature dependent Higgs potential.

In the second category, we shall investigate Randall-Sundrum extra dimensional models with the Goldberger-Weise stabilization mechanism by a scalar field. In such models there is in four dimensions a new scalar field, the radion, which acquires a temperature dependent vacuum expectation value. The electroweak phase transition in such models has been studied in a seminal paper [47] but only in the limit of small back-reaction of the stabilization mechanism on the metric. For theories a strong back reaction the question has not been studied systematically [48, 49]. Similar investigations will be carried out in composite Higgs models with additional fields acquiring temperature dependent vevs [50].

An important question for extensions of the SM with 1st order phase transition is the vacuum stability [51] which will also be investigated.

3-2. *Developing analyses of $pp \to hh$ focusing on 2-τ + 2-b and 4-τ final states using ML.*

Through collaboration with the theory team, a CP sensitive variable will be constructed and used as a tool to discriminate the di-Higgs signature from the other SM background. Bergen group has experience in innovative methods of reconstructing the mass of a heavy particle decaying to τ leptons in events with no additional missing energy. The final states with τ leptons have certain not yet exploited advantages. We plan to use them in the following way:

- Correlating mass information and spin information encoded in τ hadronic decays to construct variables sensitive to the spin of the Higgs boson. This will improve ZZ and Zh background rejection.

- Constructing CP-sensitive variables to distinguish hh production from possible hA production, where A is a BSM Higgs-boson-like particle with a different CP.

- Embarking on a difficult $hh \to \tau^+\tau^-\tau^+\tau^-$ final state could be the only way to tackle the CP of the final state. In the SM the cross-section for hh production is small due to the negative interference of two production mechanisms, and only one of these mechanisms is sensitive to the triple-Higgs coupling. BSM processes can enhance hh production. In some kinematic regions related to the CP of the final state the amplitude squared of the diagram sensitive to either to the triple Higgs coupling or to BSM contributions can dominate. Assignment of the τ lepton to the right Higgs boson is ambiguous thus the mass reconstruction is difficult, and thus the rejection of ZZ background. However it can be possible in the boosted regime (h produced with a relatively high transverse momentum) and correlating mass and spin information. ML methods are a promising tool to tackle this problem.

3-3. *Derving general conclusions on probing the EWPT by the di-Higgs production process.*

Following the introduced categorization into the two classes of extensions of the SM with 1st order EWPT, we shall determine the theory and parameter spaces where the EWPT can be and cannot be probed at the HL(HE) LHC. In the second case, we shall look (theorists+experimentalists) for a potential other collider signatures and, on purely theoretical side, estimate the magnitude of gravitation waves as a complementarity to colliders.

Task 4: Probing new sources of CP violation in the Higgs-fermion sector (1-24th month).

Team: Krzystof Rolbiecki, Janusz Rosiek, Kazuki Sakurai (Warsaw), Bjarne Stugu, Anna Lipniacka, Post-doc, PhD student (Bergen)

Coordinators: Janusz Rosiek, Bjarne Stugu

4-1. *Constructing ideal variables that are calculable from lab frame observables and sensitive to the CP violation in the* $h \to \tau^+\tau^-$ *and/or* $pp \to ht\bar{t}$ *processes.*

Experimental methods used here will be similar to those used in the Task 3: Correlating mass information and spin information encoded in τ hadronic decays to construct variables sensitive to the spin, CP state and the mass of the Higgs boson. here there are several methods worth testing in combination with the ML use. One of them is to use the transverse boost of the Higgs boson to distribute missing energy from neutrinos between the taus. Another one, developed in Bergen, is to boost the system to the Higgs boson rest frame using the accolinearity of the visible product from the decays of the taus. Two other methods, one of them co-authored by Bergen use either azimuthal angle between momenta of visible product from τ^+ and τ^- decays, as one of the variables fed to ML or vertex reconstruction of $\tau^\pm \to \pi^\pm\pi^\pm\pi^\mp(\pi^0)\nu$ decays to constrain the neutrino momentum and to fully reconstruct the Higgs boson kinematics.

4-2. *Performing realistic MC simulation including detector effects and estimates projected sensitivities to the CP phase of the* h-τ-τ *and* h-t-t *couplings at various collider options (HL-LHC, HE-LHC).*

Here we will perform the similar steps as in the Task 2:

- Work with the existing ATLAS Run 2 data/simulations, to chose the best ML method to combine τ spin information, CP sensitive variables and mass sensitive variables to reconstruct the Higgs boson CP state. Test the sensitivity improvement vs presently used methods.
- Adapt the results of 4.2.1 to a realistic, non-proprietary simulation of an HL LHC experiment and analyse the sensitivity.

4-3. *Investigating how these measurements will constrain models of baryogenesis.*

The theory team will estimate the minimal amount of CP violation required by the EW baryogenesis. This can be done by estimating the generated baryon asymmetry as a function of the magnitude and CP-phase of the relevant f-f-h coupling, assuming the phase-transition is strongly 1st order. With this assumption, the baryon asymmetry can be computed by solving a set of transport equations for the SM fermions going through the bubble wall from the symmetric phase. We present this result assuming the anomalous coupling is introduced (1) only to t-t-h and (2) only to τ-τ-h and (3) both. We will check the important EDM constraints, and finally compare the result with the sensitivity to the t-t-h and τ-τ-h couplings to be obtained at the HL(HE) LHC, which will tells us the testability of EW baryogenesis in terms of new CP violating sources.

Task 5: Investigating the sphaleron and mini-black hole production at the LHC and its dependence on the mechanism of the electroweak phase transition (13-36th month).

Team: Marek Olechowski, Stefan Pokorski, Kazuki Sakurai, Zygmunt Lalak, Post-doc 2 (Warsaw), Trygve Buanes, Anna Lipniacka, Konrad Tywoniuk (Bergen)

Coordinators: Stefan Pokorski, Trygve Buanes

5-1. *Through a collaboration between theoretical and experimental teams, we work out the characteristics of sphaleron and black-hole events and based on this knowledge design an analysis that can discriminate these two types of process. Machine Learning will be used.*

This is definitely a “high risk/high gain” part of the project. The visible final state of both sphaleron and microscopic black holes is highly model dependent. Classical “Hawkings” regime applies only to microscopic black holes with a relatively high mass (several TeV) while the quantum regime is hard to calculate. In addition, to reliably train ML methods one needs signal-like and a background-like sample in the real data, in addition to the simulated data. In addition to QCD multijet, the background will arise from $t\bar{t}+$jet production and $VV+$jet production in hadronic final states. One can endeavor to construct a signal like sample by replacing b-jets in real $t\bar{t}+$jets events with light quark jets or gluon jets (black-hole like signal) or hadrons in jets with leptons (sphaleron-like signal). However, if we are able to construct a reliable method to distinguish sphalerons from black holes and background even for a limited class of models this will be a spectacular success of this project.

To achieve this goal, we shall examine several approaches to this problem. One is the charge asymmetry of the produced leptons. The anomaly of B+L predicts that the final state contains 3 anti-leptons. If they are charged leptons, this gives an excess of positively charged leptons against negative ones. However, this excess will be diluted by the leptons produced by decays of an anti-top-quark and many W and Z bosons in the events. Another useful handle is the transverse momentum distributions of jets and leptons. In the sphaleron case, their distributions will be determined by the phase-space up to the absolute scale, which may be sensitive to the Higgs-EW potential. On the other hand, in the mini black hole case they will obey the thermal distribution. In order to detect these subtle differences, the machine learning technique will be used.

5-2. *The theory team investigates how the BSM physics relevant for the EW phase transition changes the cross-section and kinematics of sphaleron and black-hole events.*

The sphaleron event rate can in principle be estimated by means of the path integral method in the instanton background. If new physics modifies the shape of the Higgs-EW potential, the event rate gets modified through the instanton field configuration. The theory team first investigates this effect. The second important effect arises if new physics contains new fermions charged under the EW gauge symmetry (e.g. Wino and Higgsino in SUSY models). Since the sphaleron process changes the Chern-Simons number, the chiral anomaly forces all EW fermions to be produced in the chiral symmetry limit. Since this symmetry is explicitly broken by the mass of new fermions, the production rate of new fermions depends on its mass. The theory team will investigate the effect of the new EW fermions in terms of the sphaleron production rate and its event characteristics due to the inclusion of new fermions in the final state. The theory team also investigate the event characteristics of the mini black holes in RS scenario. The mini black hole production and its decay in this scenario are less studied compared to those in the large extra dimensional models. The goal is to understand the difference of black hole events between these scenarios and introduce appropriate modifications to the MC event generator for the black hole production [52]. In particular, we shall study the mini-black hole production in RS scenarios with strong back-reaction of the stabilization mechanism on the 5-dimensional metric, which may be relevant for the EWBG.

5-3. *The experimental team estimates the necessary collider energy and luminosity to discriminate sphaleron and black-hole events and determine sensitivities to probe new physics.*

We examine the analysis developed in **5-1** with various choices of collider energy and luminosity and estimate the necessary collider performance to discriminate the sphaleron and black-hole events. We also study how those colliders can constrain models of EW phase-transition via sphaleron processes.

Task management: The project realization will start with a kick-off meeting in Bergen. There will be theory+experiment coordinator for each task, in permanent contact with each other. Task members will have monthly video meetings. Meetings in person will be organized by task coordinators. We plan to have one full project conference per year. The two PI’s will be in permanent contact with each other and will review each task separately in a video meeting with task coordinators each month. Particular attention will be paid to the experiment-theory interaction, with frequent mutual visits in Warsaw and Bergen. Post-docs and PhD student will be deeply involved in the research in close collaboration with the rest of the team.

3.2 Role of the participating team members

The team is built of two groups with complementary expertise: the experimental group from Bergen and the theory group from Warsaw. The members of the Bergen group belong to the ATLAS collaboration but their activity in this proposal will not interfere with their participation in the ATLAS collaboration. Trygve Buanes is an expert in ML methods and BSM physics with τ leptons in the ATLAS experiment data. Bertrand Martin dit Latour is an expert in τ and jet physics and in computing methods. Therese Berge Sjursen is an expert in ML,experimental τ and Higgs physics. Bjarne Stugu has strong expertise in τ, Higgs and jet physics. Konrad Tywoniuk is a very high class specialist in jet physics.

The theory Warsaw group is very well balanced in its expertise. Krzysztof Rolbiecki and Kazuki Sakurai have strong experience in applying theoretical ideas to the data analyses and in proposing new data analysis techniques. Janusz Rosiek is an expert in Effective Field Theory techniques and in building new computer codes for analytical calculations. Marek Olechowski, Stefan Pokorski and Zygmunt Lalak have very strong expertise in investigating BSM theories closely related to the scientific profile of this project, with a very high record of achievements.

- associate professor Trygve Buanes (UiB, experiment):
  Contributing to Task 1, Task 2, Task 5

  Trygve Buanes has a double PhD from the University of Bergen (2008), one in related to B-meson physics in the ATLAS experiment, and another in statistical physics applied to petroleum technology. Since 2017 he is an associate professor at the Department of Computing at the Western Norway University of Applied Science, and an ATLAS member via association with the University of Bergen, Department of Physics and Technology. He presently develops ML methods to search for BSM physics with τ leptons in the ATLAS experiment data. Since 2018 he is co-supervising three data science master students together with Therese Sjursen. He was a co-organizer of 2016 CERN's European School of High Energy Physics, that took place in Skeikampen, Norway. Trygve Buanes has an ample experience in searches for DM both in ATLAS and in the CTA collaborations. In ATLAS he worked among others on pMSSM scan exploiting the data on Electroweak Production of DM (Buanes, ATLAS scan), in CTA he worked on monochromatic photon signature of DM annihilation. He works as well on DM signatures with taus, and presently develops ML methods in this direction. This makes him an ideal candidate to work on Task 1 and Task 2. When it comes to Task 5 he will be responsible for the ML part of it, where he has the the most ample experience in our group.

- Professor Zygmunt Lalak (UW, Theory)
  Contributing to Task 3, Task 5

  Zygmunt Lalak has obtained his PhD degree from the Faculty of Physics, University of Warsaw (1991), Doctor of Sciences degree (DSc) from the Faculty of Physics, University of Warsaw (1999) and the title of the Professor of Physics from the President of Poland in 2008. Since 1985 at the Faculty of Physics, University of Warsaw, since 2003 professor, and since 2013 full professor. Since 2016 Deputy Dean of the Faculty, supervising scientific research and responsible for scientific grants run in the Faculty. His main research area is physics beyond the Standard Model and particle cosmology. He contributed to the field of supersymmetry and to the development of the theories with extra spatial dimensions. More recently he has lead the research group focusing on the issue of the stability of the electroweak vacuum and on inflationary scenarios in theories with higher powers of the curvature (e.g. Starobinsky inflation) as well as on the related production of gravitational wave signals. He has supervised 8 completed PhD degrees and numerous B.Sc./Master degrees. His expertise is perfectly suited for theoretical aspects of Task 3 and 5.

- senior researcher Dr. Bertrand Martin dit Latour (UiB, experiment):
  Contributing to Task 1 and Task 3

  Bertrand Martin dit Latour has a PhD (2008) from Laboratory of Subatomic Physics and Cosmology (LPSC), Grenoble, France, with thesis on top quark physics within D0 Collaboration at the Tevatron. He is a permanent researcher at the Department of Physics and Technology, University of Bergen since 2014. He has/had several positions of responsibility within the ATLAS Collaboration: ATLAS Tau Working Group Convener (presently), ATLAS Derivation Production Manager (data and simulation samples), ATLAS Tau Trigger Coordinator, ATLAS Online Software Coordinator for the Liquid Argon Calorimeter. He coordinates presently the ATLAS "SUSY τ +X" working group and coordinates a task on New Particle Searches within Norwegian HEPP project. He is as well responsible for local ATLAS computing resources at UiB (Tier 3). He co-supervised 6 PhD students in various ATLAS collaborating institutes. He has given four invited plenary talks at international conferences within the last 5 years. Bertrand Martin's experience with the ATLAS trigger system and Calorimetry make him and ideal candidate to work on task 1, where both of this aspects will be important. Bertrand Martin presently co-supervise a PhD project with the search for sbottom pair production, where the final state contains $(bb + \tau\tau)$ arising from the decays the two Higgs boson. This is nearly the same final state as we will look at in the Task 3, thus Bertrand will be a valuable contributor to this task.

- professor Anna Lipniacka (UiB, **Norwegian PI**, experiment):
  Contribution to Task 1, Task 2, Task 5

- professor Marek Olechowski (UW, theory):
  Contributing to Task 1, Task 3, Task 5

  Marek Olechowski obtained PhD degree in 1988, habilitation in 1996 and professor title in 2012. He has been employed at Faculty of Physics, University of Warsaw since 1983, where he works now as a full professor. His long term appointments were: Max Planck Institute in Munich (1988/89/90 and 2008/2009), University of Heidelberg (1990 and 2006/07), CERN (1994 and 2012/13), INFN Turin (1995/96), Technical University Munich (1996/97/98), Bonn University (2001/02), Ludwig Maximilian University Munich (2008/09). He has expertise in a wide range of BSM physics. He is a coauthor of many well known papers on models with warped extra dimensions and several papers on inflation. Recently he has been working also on phase transitions in Randall-Sundrum-like models [49]. This makes him a perfect candidate for a coordinator of Task 3. He is also an expert on Dark Matter and SUSY. Thus, he will be an important member of teams designated to Tasks 1 and 5.

- professor Stefan Pokorski (**Polish PI**, theory, UW):
  Contributing to Task 1 , Task 3, Task 5

- Dr hab. Krzysztof Rolbiecki (UW, theory):
  Contributing to Task 1, Task 2, Task 4

  Krzysztof Rolbiecki has PhD (2008) from the Faculty of Physics, University of Warsaw. After receiving the doctoral degree he was a postdoc at the Institute for Particle Physics Phenomenology (IPPP), Durham University, DESY Hamburg and the Autonomous University of Madrid. Since 2016 he is an assistant professor at the University of Warsaw. His research interests cover supersymmetric models and other extensions of the Standard Model, with particular emphasis on the collider phenomenology at the LHC and lepton-positron colliders. He is a co-author of the computer code `CheckMATE` that performs an automated comparison of an arbitrary BSM models with LHC data. He is also involved in projects that apply ML methods in particle physics, for example the `DeepXS` computer program that approximates production cross sections of supersymmetric particles. He co-supervised 4 PhD students during his postdoctoral fellowships.

- professor Janusz Rosiek (UW, theory)
  Contributing to Task 2, Task 4

  Janusz Rosiek received Ph.D. in 1993 from the Physics Department of the University of Warsaw. His thesis discussed effects of radiative corrections to masses and couplings of Higgs bosons in supersymmetric models and how they can affect Higgs searches at LEP and LEP2. He spent 6 years at postdoc positions at the University of Valencia (1994), University of Karlsruhe (1995-96, Humboldt Fellowship) and Technische Universitat Munchen (2000-02, 2004). Since 2013 he is employed as the professor in the Institute of Theoretical Physics of the Physics Department of the University of Warsaw. At present his research interests concentrate on theoretical aspects of the Effective Field Theory extension of the Standard Model (SM EFT) and on creating calculational tools. Within last 5 years, he was a main developer of publicly available computer packages for the high-energy physics – `SUSY_FLAVOR` (flavor transitions in the MSSM), `MassToMI` (flavor expansions general in BSM models) and `SmeftFR` (Feynman rules generator for the SM EFT). He is a PI of one of Polish National Science Centre (Narodowe Centrum Nauki) OPUS10 series grant (starting 2016). He has supervised 8 completed Cand. Scient/Masters degrees and 1 completed PhD degree and has few more current students.

- associate professor Therese Berge Sjursen (UiB, experiment):
  Contribution to Task 2 and Task 4

  Therese Sjursen has PhD (2014) from the Department of Physics and Technology, University of Bergen. Her thesis concerned searches for supersymmetric particles in the final states with τ leptons at the ATLAS Experiment. Since 2017 she is an associate professor at the Department of Computing at the Western Norway University of Applied Science, and an ATLAS member via association with the University of Bergen, Department of Physics and Technology. She presently develops ML methods to search for BSM physics with τ leptons in the ATLAS experiment data together with Trygve Buanes. Since 2018 they are co-supervising three data science master students focusing on ML methods. She has an education as well in medical imaging, and was working as an analyst in the Haukeland Hospital in Bergen 2016-2017. She was a fellow of the research school "ML in High Energy Physics" in DESY, 2019. She co-organized several topical workshops, among others "From Higgs to Dark Matter", 2014, Geilo, Norway. She has an active outreach profile, with popular lectures and outreach events organization. Therese had a strong contribution to the ATLAS pMSSM scan and did a pioneering work on τ reconstruction in her PhD thesis. Presently, she works closely with Julia Djuvsland who is MSCA-IF researcher in Bergen, responsible for the mono-Higgs search. This experience fits very well to the task 2. In task 4, Therese's experience with τ reconstruction and ML methods will be very valuable.

- Dr hab. Kazuki Sakurai (UW, theory):
  Contributing to Task 1, Task 4, Task 5

  Kazuki Sakurai has PhD (2009) from the Department of Physics, Nagoya University (Japan). After receiving the doctoral degree he was a postdoc at University of Cambridge, DESY Hamburg, King's College London and IPPP, Durham University. Since 2017 he is an assistant professor at the University of Warsaw. His research interests cover model building of dark matter and phenomenology beyond the Standard Model, and collider phenomenology on Higgs, Dark Matter and non-perturbative Standard Model processes. He is an author of the computer code `Fastlim` that calculates the exclusion p-value for supersymmetric models against the LHC data. He has been supervising a PhD student under his research grant. Recently, he has studied the collider implication to the dark matter simplified models, which makes him a perfect candidate for a coordinator of Task 1. He also studied the $pp \to ht\bar{t}$ process with CP violating the t-t-h coupling, and sphaleron productions at hadron colliders with `Herwig-7` event generator. He will, therefore, be an important team member for Tasks 1 and 5.

- professor Bjarne Stugu (UiB, experiment):
  Contributing to Task 3 and Task 4

Bjarne Stugu has a Doctor of Science degree from the Department of Physics, University of Oslo (1987) and is employed at the Department of Physics and Technology, University of Bergen since 1992, and as a full professor since 1999. He was a project leader of Norwegian ATLAS Construction project (2000-2005) and presently coordinates a work-package on the pixel detector upgrade within the Norwegian LHC upgrade program (NORLHC). He was responsible for τ reconstruction and τ polarization measurement in the DELPHI Detector at LEP (1992-2001). He is an active member of the ATLAS Collaboration since 1995 with currently active in analysis of Higgs boson in the $\tau^+\tau^-$ channel, and in study of the $\tau^+\tau^-$ system in general. He has supervised 21 completed Cand. Scient/Masters degrees and 5 completed PhD degrees. Bjarne has a lifetime experience with τ reconstruction both in ATLAS and DELPHI collaboration and has several innovative ideas on mass reconstruction of $\tau^+\tau^-$ system. He strongly contributed to the first measurement of the $h \to \tau\tau$ cross-section with ATLAS. He supervised PhD thesis of Steffen Maeland (2018). Thus his expertise matches beautiful Task 3 and Task 4.

- special researcher Dr. Konrad Tywoniuk (UiB, theory)
  Contributing to Task 1 and Task 5

  Konrad Tywoniuk has a PhD (2008) from the Department of Physics, University of Oslo in the subject of "Hard and Soft Physics in pp, pA, AA collisions". He was a CERN fellow in 2015-2018 working on jet substructure and parton energy loss in QCD matter. Since the end of 2018 he is a PI in prestigious starting grant from Bergen Research Foundation "Thermalizing jets: new aspects of non-equilibrium physics at colliders" and employed as a researcher at the Department of Physics and Technology, University of Bergen. He has co-organized five international topical workshops within the last 3 years, and given two invited plenary talks on international conferences within this period. He has acted as a referee for Journal of High Energy Physics, Physical Review C, Physical Review D, Physics Letters B, European Physical Journal C, Journal of Physics G, Physica Scripta and served as expert reviewer for National Science Centre (Narodowe Centrum Nauki) OPUS17 and PRELUDIUM17 grants, Poland. Konrad Tywoniuk is an expert on understanding and simulating jets. His expertise will be very valuable for Tasks 1 and 5.

- Post-doc (UiB)
  Contributing to Task 2, Task 3, Task 4

- Post-doc 1(UW)
  Contribuing to Task1, Task 2

- Post-doc 2 (UW)
  Contributing to Task 5

- Post-doc 3 (UW)
  Contributing to Task 3

- PhD student (UiB)
  Contribution to Task 3 and Task 4

The postdocs and the PhD student will have assigned to them one more experienced researcher to each, as the closest collaborator and mentor.

3.3 Added value of the international cooperation

There are two aspects of the proposed international collaboration. One is that there is a great added value of the proposed collaboration between an experimental and theoretical university groups in the research field of this project. The other aspect is that in the beyond the Standard Model physics the two partners are for that purpose the partners of choice in Norway and Poland, perfectly complementing each other.

The Bergen experimental group is a part of the ATLAS collaboration and participates in the data analyses and the sensitivity prognoses for the LHC upgrades of the whole collaboration. ATLAS has a multitude of structures for its interaction with theorists, including participation of selected theorists as coauthors of ATLAS papers (Short Term Association, STA). The Warsaw theorists have access to the ATLAS open data and to the published sensitivity prognoses, to confront their work. The proposed collaboration goes far beyond this framework, while it is meant not to interfere with the Bergen group participation in the ATLAS collaboration. The goal is to write joint Bergen-Warsaw publications using realistic but not proprietary simulation of experimental capabilities. We see our collaboration as focused, from the experimentalists side, on searching for not yet fully explored signatures and the methods of analyses, as well as new ways of presenting their results, inspired by the Warsaw theorists suggestions. One can call it as developing some prototype ideas. From the theorists side, the help is needed to achieve realistic sensitivity estimations for testing models. We will jointly embark on finding new ways of testing a broad spectrum of existing models rather than testing models one by one. The proposed collaboration at the level of small university groups guarantees strong feed-back and quick back-reactions in facing those questions.

More specifically theory group can assist an experimental ATLAS group in:
– pin-pointing experimental signatures characteristic for a broad class of the Standard Model extensions;
– construction of cross-check signatures in case if one of the searches shows a discrepancy with Standard Model prediction (see examples in the monojet signature below);
– constructing a projection on how the signal should be seen in another type of observation, for example in an indirect search for Dark Matter in the Cerenkov Telescope Array observatory or in direct Dark Matter search experiments.

Bergen ATLAS group can assist a theory group in:
– constructing a realistic simulation of the experimental response to a given model signature;
– realistic interpretation of eventual deviations from the Standard Model observed in the experimental data;
– understanding of capabilities of future experiments and experimental limitations of present results;
– last but not least, in exploitation of the presently substantial sample of ATLAS open data for the educational and training purposes.
All above aspects represent an added value of direct collaboration of an experimental and theoretical university groups.

We would also like to stress that regular scientific contacts between the two PI's exist already for many years, with regular personal meetings at CERN. Both have been frequent visitors there. A joint project between the two groups is a natural consequence of those contacts and would significantly increase the contribution of both groups to the European research.

3.4 Possible societal impact of development of ML methods in HEPP

ML methods have more and more societal impacts, as they are increasingly used for example in face and object recognition in situations impacting safety of individuals and in medical diagnostic image recognition. Understanding the bias and reliability of the multivariate methods (neural networks, boosted decision trees, AI) has been a part of high energy particle physics (HEPP) culture since long. Comparing the results with a standard cut-and-count based selection methods, and understanding the "source" of decisions made by ML is a part of this culture. Thus the HEPP community has been aware of biases and demanded to get rid of the biases which affected the analysis. The general data science community has more of a "whatever the data reflects" or "fairness" approach, which has only recently become an important part of the public ML-discussion. The main reason for this discussion is that race and gender biases are being detected and blown up on newspaper front pages - not because of subject matter expertise. In other words, this biases most probably affect not only gender and race in facial recognition, but other applications of ML, just have not been detected yet. These biases are soon affecting our everyday safety, and are coming presently to sight only after a spectacular crashes (example 7/05/2016 crash in Williston, Florida due to Tesla Model S autopilot failing to recognize white tractor-trailer).

Second immensely important point: Explainability. There is a whole debate out in the commercial data science community concerning what "explainability" is and whether it's important. Physicists are trained to understand the underlying drivers of ML decisions. In the HEPP community, if one manages to find a signature but one has no idea what does it really come or what is the real cause of it, the job is not finished yet. This is not the norm in the data science community at all. This is something the HEPP community had to think about for a long time, while the commercial data science community is barely starting to grapple with it. Thus the development of ML methodology within HEPP community has much to offer in terms of societal impact. This is reflected in a strong recruitment of HEPP graduates with ML experience into commercial data community. One of them is Dr Inga Struemke (inga@strumke.com), PhD 2019 at the Department of Physics an Technology, University of Bergen, presently Data Manager in the section of Responsible AI, PwC, Oslo. Dr Struemke volunteered to be a knowledge transfer consultant for this project.

This project will further develop ML reliability standards.

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