Initial abstract from Arnaud:

Following the discovery of a new spin-0 particle at the Large Hadron Collider by the ATLAS and CMS collaborations in 2012, the Nobel prize in physics was awarded to Profs Englert and Higgs in 2013 for the "theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles". The measurements of the properties of the Higgs boson have so far confirmed the predictions of the Standard Model, however the actual shape of the Higgs potential has not been measured experimentally yet. The research project of this application aims at gathering experimental information at the Run-3 of the LHC to draw conclusions about the Higgs potential. For this purpose, a central activity will be to constrain the Higgs self-coupling parameter as it determines the shape of the Higgs potential. According to the Standard Model predictions, the Higgs boson has the unique ability to couple to itself, which should result in the simultaneous production of two Higgs bosons in high-energy proton-proton collisions. However, the predicted event rate is very small and the Run-3 dataset should not allow to find evidence of Higgs boson pair production, unless new physics manifests itself in the Higgs sector, e.g. by modifying the Higgs boson self-coupling (and thereby the shape of the Higgs potential), by introducing new vertices involving Higgs bosons (as predicted in Effective Field Theories where the scale of new physics is beyond that observable in experiments) or through heavy resonances decaying into pairs of Higgs bosons. Several research groups in Sweden already play a leading role in experimental searches for Higgs boson pairs at the LHC, and we want to expand on the experience acquired in the field to probe the fundamental question of the shape of the Higgs potential, in a close collaboration between experimentalists and theorists + we need some words about implications for the vacuum stability, compositeness (?), added value, etc…

Input from Stefano:

The triple Higgs coupling is a crucial key to unlock the door towards understanding the hierarchy problem, which best solutions are to date Compositeness and Supersymmetry. In (unbroken) Supersymmetry, the triple-Higgs coupling is the gauge coupling, so to measure or constrain it (through experimental searches or theoretical self-consistency) to be so would be a crucial hint in this direction. As for Compositeness, a key feature is the strong correlation between the (top) Yukawas and the Higgs self-couplings, since they can both be generated by the breaking of the pNGB shift symmetry. Finally, as a common element, Higgs pair production captures both the quartic couplings Higgs-Higgs-stop-stop (Supersymmetry) & Higgs-Higgs-heavy-top-heavy-top (Compositeness), topologies which do not appear in the SM and which are intrinsically different in these two theoretical constructs, as in one case they are induced by top scalars (Supersymmetry) and in the other case by top fermions (Compositeness).

Finally, to invoke both Supersymmetry & Compositeness as theoretical frameworks would also be instrumental to build upon and further the current KAW grant (which covers both Supersymmetric and Composite top physics) quite seamlessly. In fact, there is a nice element of inheritance that one may invoke to justify the new grant in relation to the current one, that lessons learned from the latter can be fed into the former (as the same Supersymmetric/Composite top-Higgs interactions studied now would enter Higgs-pair physics too). Last, but not least, we could invoke timeliness in our bid: ie, while the current grant is making progress already with existing Run 2 data the future grant will need Run 3 ones, so that it is then natural that one should follow the other. Indeed, as discussed in Stockholm, in a KAW bid we should make sure to convey the message that the two pieces of research are certainly connected but also very different in scope, if we want to succeed this time around too.

===

Combined abstract (my attempt)

Title: The Measurement of Universal Cosmology and New Matter through the Higgs Boson Self-Coupling

Question this grant must address: To discuss

Part I: Physics Motivation

Following the discovery of a new spin-0 particle at the Large Hadron Collider by the ATLAS and CMS collaborations in 2012, the Nobel prize in physics was awarded to Profs Englert and Higgs in 2013 for the “theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles”. In more recent years, the null observations of any hints of new matter at the LHC has led the community to question the validity of theories such as supersymmetry (SUSY) as viable extensions to the Standard Model (SM). A new approach is required, and a precision understanding of the Higgs boson could shed new light on the fundamental dynamics of physics beyond the Standard Model. While the current measurements of the production rates and couplings of the

Higgs boson to SM particles have so far confirmed the predictions of the Standard Model, the global shape of the Higgs potential has not been measured experimentally yet. It is this property of the Higgs which offers a unique gateway into new physics, and directly connects fundamental particle physics to the broader question of the cosmology of our early universe, in particular the origin of universal inflation. To access such physics a central activity will be to constrain the Higgs self-coupling parameter as it determines the shape of the Higgs potential. According to the Standard Model predictions, the Higgs boson has the unique ability to couple to itself, which should result in the simultaneous production of two Higgs bosons in high-energy proton-proton collisions, the so-called "di-Higgs" production. One of the aims of this project will be gathering experimental information at the Run-3 of the LHC with the long-term goal of obtaining the first statistically significant observation of the direct production of the di-Higgs final state. We propose two complementary tracks, which seek to address fundamental and high-profile questions at the heart of understanding our existence.

Track 1: Di-Higgs as a Probe of the Global Potential and Universal Cosmology

Recent Higgs and top mass measurements [REF] indicate that we inhabit a universe which exists on the cusp of stability and metastability. New probes are required to further assess the cosmological stability of our universe, and the measurement of the di-Higgs process provides such a window in the form of the Higgs self-coupling. By using di-Higgs events to constrain the Higgs self-coupling, we aim to provide the first probe of the global shape of the Higgs potential, which will greatly extend our understanding the fundamental vacuum in which the Higgs fields resigns, whether this is the universal "true" vacuum, or if indeed our cosmological fate is more accurately described by a metastable, "false" vacuum [REF]. This project will unite LHC searches across bbyy, bbtautau, and multi-lepton di-Higgs final states to push the discovery boundaries of the Higgs self coupling with LHC data and address the question head-on of how consistent the self-coupling is with the SM and the macroscopic cosmology of our universal reality.

Track 2: Di-Higgs as a Probe of Naturalness, SUSY, Compositeness, and Beyond

The triple Higgs coupling is a crucial key to unlock the door towards understanding the hierarchy problem, where the other best solutions to date — namely, Compositeness and Supersymmetry — are becoming increasingly constrained by LHC data.. In (unbroken) Supersymmetry, the triple-Higgs coupling is the gauge coupling, so to measure or constrain it (through experimental searches or theoretical self-consistency) would provide an invaluable probe of supersymmetric physics scenarios. To further complement these studies, Compositeness comprises a key feature of there exists a strong correlation between the top Yukawa couplings and the Higgs self-coupling, since they can both be generated by the breaking of the pseudo-Nambu-Goldstone boson shift symmetry [REF]. Crucially, the Higgs self-coupling provides an idea link between these two well-motivated theoretical extensions to the SM: Higgs pair production captures both the quartic couplings Higgs-Higgs-stop-stop (Supersymmetry) & Higgs-Higgs-heavy-top-heavy-top (Compositeness), topologies which do not appear in the SM and which are intrinsically different in these two theoretical constructs, as in one case they are induced by top scalars (Supersymmetry) and in the other case by top fermions (Compositeness). It is therefore apparent that the nature of SUSY, compositness, and therefore the implications for naturalness and fine-tuning in our universe [REF] can be directly assessed through precision measurements of di-Higgs production at the LHC. Finally, the model-independent approach of Effective Field Theory (EFT) will be employed in the study of di-Higgs production.

Several research groups in Sweden already play a leading role in experimental searches for Higgs boson pairs at the LHC, and we want to expand on the experience acquired in the field to probe the fundamental question of the shape of the Higgs potential, in a close collaboration between experimentalists and theorists, through a common working group connecting Stockholm, KTH, Uppsala, Lund, and Chalmers (?) Establishing a link between experimentalists and theorists will generate a natural symbiosis in which the di-Higgs searches at ATLAS can be directly interpreted within the theory community. Furthermore, a major goal of this collaboration will be the study of new models, beyond SUSY, compositeness, and heavy resonances, which could shed light on the nature of the eventual observation of the di-Higgs final state and therefore reveal the deepest secrets of the fundamental building blocks of our universe, as well as its underlying cosmology.

This project will complement the existing SHIFT grant, by further extending the question of addressing naturalness and beyond SM physics through direct measurements of the Higgs boson, in contrast to direct measurements of stop production at the LHC.

Part II: Deliverables and Timescales

- Establishing Sweden as a leader in experimental searches for di-Higgs final states by the end of Run 3 of the LHC (~2024), in time for the first statistically significance self-coupling measurement and test of universal cosmology at the HL-LHC (~2026). This will be achieved through the rapid expansion of the Swedish di-Higgs Working Group and the recruitment of several PhD and postdoctoral research fellows.
- The publication of Run 3 summary papers across the bbyy, bbtautau, multi-lepton and HH combined limit LHC papers by 2024.
- The development of non-minimal theoretical models beyond SUSY and compositeness, in the period 2022-2024, with deployment of those models in di-Higgs searches using Run 3 data and beyond.