# Executive Summary

# MITP Scientific Program
# "Fundamental Composite Dynamics: Opportunities for Future Colliders and Cosmology"

Aug. 26. - Sep. 6. 2019, Mainz Institute for Theoretical Physics, Johannes Gutenberg University

The main goal of this MITP program was to bring together experts from various communities under the flag of understanding the role of strongly interacting theories in particle physics and cosmology, with special focus on theories beyond the Standard Model (BSM). The expertise from the participants ranged from Dark Matter to field theory in the strong coupling regime, from model building of Composite Higgs to Cosmology, from collider experiments to Lattice calculations, from collider physics MonteCarlo and recasting tools to gravitational waves. The great array of interests, combined with the flexible schedule, created a fertile environment for discussion and exchange of ideas. We organised one informal topical talk per day, in the morning, often co-chaired by two speakers presenting the subject in a critical and provocative way. In the afternoons, time was dedicated to collaborative work and discussion sessions, often organised by the participants themselves. A few afternoon talks were proposed by the participants. All in all, the program was a great success thanks to the many discussions we had during the two weeks. Also, during both weeks there was a relatively important number of experimentalist participants, fostering in particular discussions related to experiments and phenomenology.

Many topics were touched upon, a comprehensive description of which goes beyond a summary. The main physics questions that were raised and vividly discussed during the workshop are listed below:

- *What are the key ingredients for natural composite Higgs models? How can solid predictions be made for HL-LHC and future colliders?*
- *Are there any hints for composite dynamics in the data? Are there promising channels which could have been missed, so far?*
- *How can we best provide event generation, simulation and recasting tool sets for strong BSM dynamics at colliders?*
- *Are there new fundamental theories that have not been studied yet? Is asymptotic freedom a must?*
- *What are the cosmological implications of composite dynamics at the TeV scale?*

- *What can Lattice results add to our understanding of strongly interacting BSM models? What is the current status? Which theories should be studied on the Lattice?*

## Underlying theories & model building

Defining a microscopic dynamics or UV completion that can predict observed (or observable) New Physics effects at low energy is a crucial step if we want to construct reliable BSM scenarios. This will also allow us to correlate observations (and limits) coming from different types of experiments (including Cosmology) and colliders at different energy scales. One such example was discussed by W.Porod (28/8): he reviewed the status of the flavour anomalies in the B-meson physics and lepton universality, and discussed recent UV complete models that have been proposed. They include models with extended gauge symmetries, as well as one model based on composite dynamics. On a different stage, afternoon sessions discussed interesting developments in the construction of UV complete theories for composite Higgs dynamics. This was done by S.Vatani and Z.W.Wang (aft. talk) at the blackboard, where one scenario based on asymptotic safety was discussed. The following week, T.Alanne and S.Blasi (aft. talk) presented some recent insights on the many-flavour asymptotic safety. Their analysis, based on a different scheme for resummation of large Nf theories, puts under discussion the presence of a UV fixed point, which seems to disappear in their approach. The discussion that ensued weighted both criticism and appreciation of the result, which does not give a final answer to the question. Lattice techniques are another way to study underlying theories (see next topic), and work in progress is being done in answering the question of UV safety. If confirmed, this class of theories could offer a new way to build truly UV complete theories, which can be extended to any arbitrary high energy by means of the scale invariance they feature in the UV.

## Lattice results

The Lattice community achieved enormous progress in BSM Lattice calculations. However, many open questions still remain unanswered, as we do not know which underlying theory is most promising in describing a viable model. During the workshop, a number of Lattice theorists where present, representing nearly all the collaborations tackling BSM lattice computations. A.Hasenfratz (30/08) was invited to give an overview of recent results and open questions in lattice studies. One of the most important questions is the existence of an IR conformal window, where the theory “walks” : this could be crucial for some BSM theories, where the walking may generate large anomalous dimensions for some operators. In the afternoons, a discussion session was organised, over several days, where it was discussed how Lattice results can be used to give prediction for model builders, which may then be used for phenomenological studies and finally guide experimental searches. Also,

V.Drach gave an afternoon talk. One of the most important questions regards the value of the Higgs mass in composite Higgs models, which could in principle be computed on the Lattice. The spectra of some theories are also important in guiding the experimental searches or motivate the need for a higher energy collider. However, the main hurdle we are facing now is the absence of a single preferred theory to invest the Lattice efforts. It was recalled how “expensive” lattice calculations can be in terms of computer resources, even when the precision reached in QCD is not achievable nor needed.

## Cosmology and Gravitational Waves

One of the goals of the workshop was also to connect to Cosmology and Astrophysics. In particular, composite models entail a phase transition at the multi-TeV scale, connected to the condensation of the underlying strong interactions. For composite Higgs models, this phase transition is also related to the electroweak phase transition. K.Xie (aft. talk) presented the results of a recent paper where the phase transition of composite Higgs models with top partial compositeness is discussed. The main result is that it is not easy to obtain a strong phase transition, and only some model configurations can achieve it. In particular, higher order operators are always needed to play an important role. Gravitational wave production was also discussed as a possible signature for this phenomenon. This kind of analyses is an example of how Cosmological observations (a strong phase transition may be related to the electroweak baryogenesis) could help selecting some model configurations, which could in turn be tested at colliders.
In the afternoons, there were also discussion sessions on models of composite Dark Matter.

## Phenomenology of vector-like quarks (aka top partners)

Top partners play a crucial role in the phenomenology of composite Higgs models with top partial compositeness. They are defined as new heavy quarks, with masses in the TeV range, which have the same gauge couplings on both chiralities, hence they are called vector-like quarks (VLQs). These states are actively and intensely searched for at CMS and ATLAS, where bounds of the order of 1.2-1.4 TeV are currently obtained. S.Beauceron (27/8) gave a comprehensive review of all searches at both experiments. During her talk, she was also authorised to present a new search for single production of a T’ state, which decays into top plus Higgs in the fully hadronic final state. The interest of this CMS search is that it features a mild excess at a mass of 650-700 GeV, which is hard to explain seen the current exclusion bounds on the masses.
A theory review of VLQs was also jointly presented by N.Gaur and L.Panizzi (29/8). After reviewing the general properties of VLQs, a discussion ensued on exotic decay modes. In fact, especially in composite scenarios, additional light scalars are

present, which may appear in the decays of top partners. Current searches, however, only look for decays into standard model states: for instance, T' > bW, tZ, tH are searched for. Adding other channels, like decays T' > ta, where a is a light pseudo-scalar that may decay predominantly in jets, could alter the limits. Furthermore, the presence of additional states could increase the total width of the VLQ (this was the main topic discussed by L.Panizzi).

The two presentations fuelled many discussions and activities in the afternoons. We would like to mention mainly three. First, the new results showed by S.Beauceron led to afternoon discussions aiming at finding models and signals that could explain the excess, without being excluded. This exercise was a nice example of synergy between experimentalists, theorists and phenomenologists working on MonteCarlo tool development. Second, we started a meeting that discussed a UFO file, obtained via FeynRules, which contains all the exotic decays of VLQs. We listed all the possibilities, defined a list of priorities and tasks, and started working on the implementation. The first model files including a neutral scalar or pseudo-scalar were developed during the workshop, and will be used by both experimental collaborations to study new signatures of VLQs. Thirdly, a feature of large width was discussed during the workshop: it has been observed a discrepancy in the kinematical distributions for single production of T', with further decays into tH. During the working session in the afternoon, an explanation for such discrepancy was found and solved, so that a debugged model file can now be used by both experiments to generate samples of signal events at large width. All the efforts done on this topic involved experimentalists, which were very helpful in guiding the effort of the various groups.

## Collider signatures and searches for composite models (and future prospects)

Current status and future directions for collider searches that are relevant for composite Higgs models have been a main topic of the program. Top partners are a necessary ingredient of composite Higgs models with partial top compositeness, as discussed above. However, models typically contain additional potentially light states. C.W.Chiang (2/9) discussed models that feature extended scalar sectors, like the Georgi-Macachek model that contain electroweak triplets. In the afternoons, there were several discussions on how to connect elementary and composite scalar extensions, and how to distinguish them at colliders. Also, there was a joint presentation (3/9) by G.Ferretti - theorist - and S.Gascon-Shotkin - experimentalist - on the phenomenology of light scalars in composite models. Both theoretical models and experimental searches were discussed.
The afternoon sessions witnessed several discussions, including the discussion of the potential of LHCb and of future e+e- colliders in searching for the light composite scalars. Once again, the presence of experimentalists during the workshop was crucial in fostering these discussions.

## Models and tools for composite collider physics

MonteCarlo tools are also crucial in order to connect models and experimental analyses. E.Conte and L.Panizzi (4/9) gave a presentation on the status and perspectives for BSM tools. In particular, the issue of large width VLQs in searches was discussed. The afternoon saw various discussions, including some we mentioned before: development of a master UFO implementation for exotic VLQ decays, solution of the large width implementation for T > tH. There was also a video session, to which experimentalists from ATLAS and CMS participated, where the Master UFO file was discussed: this allowed the participants to have feedback on the needs of the experimental collaborations, on the timescales, and was crucial in allowing a successful completion of the main tasks.

## Summary and legacy

In the view of the organisers, the program has been a great success, thanks to the participation of leading scientists from all over the world and belonging to various communities. In particular, we saw productive interactions and exchanges between people working in Cosmology, Model Building, Lattice gauge theories, phenomenology, development of MonteCarlo tools, and experimentalists. In particular the presence of experimentalists during both weeks was a great catalyst of discussion and of new projects. The scientific program has been kept light, with only one informal presentation per day. Often, the morning presentation merged with the discussion time, thus leading to interesting exchange of ideas. An important legacy of this workshop was the initiation of a working group on developing a master UFO model file for exotic VLQ decays, which will be of paramount importance for experimental collaborators to define searches for Run-III and generate signal events. We believe, and hope, that the program initiated new collaborations between the participants. In fact, already a few papers where published during or right after the workshop by the participants. In the appendix, we provide a partial list, knowing that more are on the way.

**G.Cacciapaglia**
**T.Flacke**
**B.Fuks**
**K.Sridhar**

*Preprints (partially already published) of participants acknowledging MITP*:

- L.Bian, Y.Wu, K.P.Xie, "*Electroweak phase transition with composite Higgs models: calculability, gravitational waves and collider searches*," **JHEP 1912 (2019) 028** [arXiv:1909.02014]

- A.Hasenfratz, C.Rebbi and O.Witzel, "*Gradient flow step-scaling function for SU(3) with twelve flavors*," **Phys.Rev. D100 (2019) no.11, 114508** [arXiv:1909.05842 [hep-lat]].

- G.Cacciapaglia, S.Vatani and Z.W.Wang, "*Tumbling to the Top*," arXiv:1909.08628 [hep-ph].

- A.Hasenfratz and O.Witzel, "*Continuous beta function for the SU(3) gauge systems with two and twelve fundamental flavors,*" arXiv:1911.11531 [hep-lat].

- A.Hasenfratz and O.Witzel, "*Continuous renormalization group $\beta$ function from lattice simulations*," arXiv:1910.06408 [hep-lat].

- B.Fuks, M.Nemevšek and R.Ruiz, "*Doubly Charged Higgs Boson Production at Hadron Colliders,*" arXiv:1912.08975 [hep-ph].

- G.Cacciapaglia, A.Deandrea, T.Flacke and A.M.Iyer, "*Gluon-Photon Signatures for color octet at the LHC (and beyond)*," arXiv:2002.01474 [hep-ph].