Strongly interacting extensions of the Standard Model on the lattice

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Final report

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1 Introduction

The OTKA-NF-104034 grant for the period 1 February 2013 - 31 January 2018 was conducted on the non-perturbative lattice investigation of strongly interacting composite Higgs models. These models are extensions of the Standard Model of particle physics in that they do not contain an elementary scalar field which in the Standard Model represents the Higgs boson. The Higgs boson in our framework is a composite particle made up of new, so far unobserved, elementary fermionic particles. These hypothetical new fermionic degrees of freedom interact via a new, so far also unobserved, gauge bosons. This new hypothetical gauge sector of the Standard Model is in many respects similar to the well established Quantum Chromodynamics. As such, it is strongly coupled, hence a non-perturbative study from first principles without uncontrolled approximations can only be performed via Monte-Carlo simulations using a lattice discretized space time.

The main motivation for our studies was two fold. First, the Standard Model, exactly because of the elementary scalar Higgs field, suffers from the Naturalness problem or in other words the fine tuning problem. The essential problem is that even though the Standard Model is renormalizable it is known that it can only be valid up to the Planck scale at which energy scale the quantum nature of gravity is expected to become relevant. Hence an energy cutoff is present in the Standard Model and the mass of the Higgs boson receives perturbative corrections origining from the cutoff $\sim 10^{19}\ GeV$. The experimentally observed mass of the Higgs boson is 125 GeV, which in the Standard Model model is a result of a cancellation of two terms which are both $\sim 10^{19}\ GeV$. This high degree of fine tuning is not seen anywhere else in Nature. The strongly interacting composite Higgs models we were interstigating solve this problem by having no elementary scalar field in the theory and the Higgs boson is rather a composite. Much the same way as there is no fine tuning problem in Quantum Chromodynamics and the hadrons are composite particles.

Second, there is overwhelming observational evidence that the visible Universe is only about 5% of the total mass of the Universe. About 2/3 of the rest is attributed to dark energy while 1/3 of the rest consists of hypothetical new particles called dark matter. The precise nature of dark matter is currently unknown. In the composite Higgs models we studied, the fermionic elementary building blocks may form not only the composite Higgs boson, but also other, so far unobserved new composite particles. If any of these models correctly describe Nature then some of these new composite particles should be visible at the Run-2 program of the Large Hadron Collider. These potential new discoveries are the primary predictions of the models. In addition, the fermionic new degrees of freedom may also form other types of new composite particles which may be identified with dark matter candidates.

As stated above the models under investigation are hypothetical and only experiments (primarily at the Large Hadron Collider) can determine whether they are viable descriptions of Nature or not. The experimental results need to be confronted with theoretical predictions in order to rule them out or rule them in. Since the models are strongly interacting a lattice approach is the only systematic and approximation free method.

2 Summary of research project and results

The primary focus of the research project has been the detailed investigation of $SU(3)$ gauge theory with large fermion content, either in the fundamental or the sextet representation. In the course of our investigations we have determined that the phenomenologically most interesting model is the sextet model with $N_f = 2$ flavors of fermions. The model with fundamental representation fermions is also interesting on its own and has been the subject of active research by several research groups. In this case the most interesting flavor number region is $N_f = 8, \ldots, 13$ which is of course much larger than in the case of Quantum Chromodynamics. The fundamental model can be used to build phenomenologically relevant models but these are somewhat more complicated and not as minimal as the sextet model. We have developed several new lattice field theory techniques specifically designed for models with large fermion content and we have applied them to both the sextet and fundamental models. The fundamental representation with lower fermion flavor number was a suitable test case because of its similarity with Quantum Chromodynamics.

The choice of models was guided by the desired phenomenological properties, namely spontaneous chiral symmetry breaking, slow running of the coupling constant, potentially small Peskin-Takeuchi S-parameter and the necessary number of Goldstone bosons. A minimal model satisfying all properties turned out to be the sextet model, but as mentioned above the fundamental models were also investigated in detail.

As far as the sextet $N_f = 2$ model is concerned we have studied in detail the pattern of spontaneous chiral symmetry breaking in the massless limit. This amounted to measuring several observables in the large volume regime (so-called p-regime) and using chiral perturbation theory to extrapolate to the massless limit [32]. The measured observables were first the chiral condensate, mass of the pseudo-scalar and vector mesons and decay constant of the pseudo-scalar meson. The applicability of chiral perturbation theory was demonstrated indicating that spontenous symmetry breaking does take place. The behaviour of the low lying Dirac spectrum was also studied in detail supplementing the information from the low energy spectrum [31]. In this regard a new technique for the efficient calculation Dirac spectral density was developed [23]. The most important result from the low energy spectrum was the measurement of the mass of O^{++} composite scalar which plays the role of the Higgs boson in the model [1,18,22,25]. Our simulations were the first on this topic. The main result is that in units of the pseudo-scalar decay constant (which sets the scale of the simulation by the desired electroweak scale 249 GeV) the $N_f = 2$ sextet model has the lowest scalar mass out of the available models that were studied by the Beyond Standard Model lattice field theory community. Needless to say that the measurement of the scalar is extremely computer time intensive because of disconnected diagrams. The low mass of the scalar was unexpected as the main criticism of composite Higgs models (of the type we investigated) has been in the past that a composite scalar will have too high a mass and can not incorporate the observed relatively low Higgs mass. Based on our non-perturbative studies this expectation proved to be premature.

For consistency the running renormalized coupling was also computed and was shown to be consistent with chiral symmetry breaking i.e. without an interacting infra red fixed point [11,24]. This computation was performed in two stages, both of which required the development of new lattice field theory techniques. First, in finite volume at exactly zero fermion mass the running coupling was computed in the so-called finite volume gradient flow scheme which was first proposed by us earlier. Within the present research program we added the necessary analytical calculations for tree-level improvement in a wide class of discretizations [15,27]. This allowed the computation of the β-function from relatively small renormalized couplings up to a certain maximal value. At the maximal value, above which a massless computation could not extend exactly because of chiral symmetry breaking, we introduced another method which is defined at finite fermion mass and in asymptotically large volume [19]. A careful infinite volume and chiral limit can then be performed leading to the β-function in the chirally broken phase. The consistency of the 2 stages serves as a powerful check of the methods and implementations. These calculations lead to the conclusion that indeed the β-funcion is small resulting in the desired slow running.

The precise embedding of the sextet model into the Standard Model is a non-trivial question and we spelt it out together with the measurement of the mass of a dark matter candidate, a nucleon-like state [7,26].

As far as the fundamental models are concerned we used these primarily as test cases for all of our new methods. Nevertheless, as mentioned in the Introduction, the fundamental models can be interesting both phenomenologically and as field theories on their own. Our finite volume running coupling scheme was implemented in the $N_f = 8$ fundamental model [13], followed by a series of works for $N_f = 12$ [2,5,17]. The latter is of a controversial nature as several research groups have announced results with opposing conclusions. We believe our most recent results on the $N_f = 12$ model stand up to the highest standards of scientific rigor and as such are superior to our competition. We have ruled out the observed infra red fixed points reported by other groups on a given renormalized coupling range to high statistical significance.

Our results for the sextet and the fundamental model, combined with other groups results for the mass of the O^{++} scalar in the fundamental models (which we did not investigate) clearly points to a curious correlation between slow running of the coupling and a low mass scalar. This correlation was conjectured previously by some groups and questioned by some other groups but only the advanced state-of-the-art lattice simulations of the past 5 years were able to give quantitative and unambiguous answers. This development is a very important unforeseen result. In order to have a deeper understanding, beyond the numerical evidence, of this correlation between slow running and light scalar we started the investigation of an effective theory containing not only the pseudo-scalar particles of chiral perturbation theory but also a scalar degree of freedom. Arguments based on scale symmetry (dilatation) allows for the construction of an effective theory which can then be applied to the numerical data. This approach is preliminary at the moment [17].

In order to explore non-abelian gauge theories further we have started an investigation of models which are expected to be conformal as opposed to spontaneously broken. In the sextet case this means $N_f = 3$ flavors, and in the fundamental case we have simulated $N_f = 14$. We have used our new running coupling method in the finite volume gradient flow scheme to compute the β-function in these two models in order to see how well conformal dynamics is captured by the method [4]. As opposed to the chirally broken models a controlled continuum extrapolation so far could not be performed unfortunately.

In 2015 I was honored to be asked to co-author a review paper on strong dynamics, composite Higgs and the conformal window by the editors of a special issue on lattice gauge theories beyond QCD [4].

As mentioned in the Introduction the incorporation of a dark matter candidate in the sextet model is a very appealing feature as dark matter is one of the most intriguing unexplained feature of the Standard Model. Since the question of dark matter is so important we have undertaken simulations in an entirely different framework, that of axions. In this setup the temperature dependence of the topological susceptibility in Quantum Chromodynamics is directly related to the mass and abundance of axions, a hypothetical dark matter candidate [5,8]. The temperature dependence of various other quantities also plays an important role in pure Quantum Chromodynamics as well as the strongly interacting composite Higgs models which were our main focus. In the latter, the critical temperature corresponds to the electro weak symmetry breaking. In the case of Quantum Chromodynamics it corresponds to the confinement transition of quarks. Before attempting to compute the critical temperature of the sextet model we have undertaken a finite temperature study of the potentially simpler Quantum Chromodynamics case [12,16,29,30].

The close connection of Quantum Chromodynamics and the sextet composite Higgs model allowed for further analogous computations which allowed for insightful comparisons. For example, the difference between the eigenvalue distributions of models inside or outside the conformal window (both at zero temperature) can be compared with the difference between the eigenvalue distributions of a single model outside the conformal window but at $T < T_c$ or $T > T_c$. In the latter case chiral symmetry is of course restored, just as it is at $T = 0$ inside the conformal window. Guided by this analogy the Dirac eigenvalue distributions were studied in high temperature Quantum Chromodynamics. A new model was proposed for the localization properties of eigenmodes as well as the distributions of eigenvalues which was successfully tested in simulations [6,10,14,28].

Even though Quantum Chromodynamics and the sextet composite Higgs model are similar in some technical sense but they are very different physically. This difference leads to vastly different patterns for the systematic errors that arise in any simulation. In order to understand these better toy models are always useful and the 2-dimensional $O(3)$ model with a ϑ-term is an example. A key feature of this toy model is the presence of a sign problem. Even though to some extent it can be brought under control by the use of cluster algorithms, we have instead undertaken a more systematic study of the sign problem and its possible solutions in a closely related problem. The problem we have investigated was the same 2-dimensional $O(3)$ model but with chemical potential [3].

In addition to the main thrust of the research program, namely numerical Monte-Carlo simulations, two analytical approaches were attempted as well. One is the use of the functional renormalization group and to what extent can new predictions be extracted beyond perturbation theory, and the other is analytical results on the 2-dimensional $O(3)$ model with ϑ-term. These approaches are currently in their preliminary phase and did not yet lead to a publication.

A key component of any large scale numerical work is the actual hardware on which the calculations are carried out. OTKA provided funding for a 16 node GPU cluster (2 GPU cards per node, total of 32 GPU cards) with InfiniBand interconnect. This platform provided a considerable fraction of the required computer resources for the project and hence was invaluable for a successful implementation.

3 Publications

The total number of published works is **33**, out of these **16** are peer reviewed journal publications and **17** are conference proceedings. The total number of citations for all of these works is **423**, the number of independent citations is **303**. In all of these publication the support of OTKA has been indicated as required.

3.1 Journal publications

1. Status of a minimal composite Higgs theory
   Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong
   Int.J.Mod.Phys. A32 2017 35 1747001
   Citations: 0 (independent: 0)

2. Extended investigation of the twelve-flavor β-function
   Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chik Him Wong
   Phys.Lett. B779 2018 230-236, arXiv:1710.09262
   Citations: 5 (independent: 2)

3. Comparison of algorithms for solving the sign problem in the O(3) model in 1+1 dimensions at finite chemical potential
   Sandor Katz, Ferenc Niedermayer, Daniel Nogradi, Csaba Torok
   Phys.Rev. D95 2017 5 054506, arXiv:1611.03987
   Citations: 1 (independent: 1)

4. Strong dynamics, composite Higgs and the conformal window
   Daniel Nogradi, Agostino Patella
   Int.J.Mod.Phys. A31 2016 22 1643003, arXiv:1607.07638
   Citations: 12 (independent: 11)

5. Fate of the conformal fixed point with twelve massless fermions and SU(3) gauge group
   Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong
   Phys.Rev. D94 2016 9 091501, arXiv:1607.06121
   Citations: 25 (independent: 22)

6. An Anderson-like model of the QCD chiral transition
By Matteo Giordano, Tamas G. Kovacs, Ferenc Pittler
JHEP 1606 (2016) 007, arXiv:1603.09548
Citations: 5 (independent: 3)

7. Electroweak interactions and dark baryons in the sextet BSM model with a composite Higgs particle
Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong
Phys.Rev. D94 2016 1 014503, arXiv:1601.03302
Citations: 19 (independent: 16)

8. Axion cosmology, lattice QCD and the dilute instanton gas
S. Borsanyi, M. Dierigl, Z. Fodor, S.D. Katz, S.W. Mages, D. Nogradi, J. Redondo, A. Ringwald, K.K. Szabo
Phys.Lett. B752 2016 175-181, arXiv:1508.06917
Citations: 52 (independent: 46)

9. On the charge density and asymptotic tail of a monopole
Derek Harland, Daniel Nogradi
J.Math.Phys. 57 2016 2 022903, arXiv:1508.03232
Citations: 1 (independent: 1)

10. Anderson transition and multifractals in the spectrum of the Dirac operator of Quantum Chromodynamics at high temperature
Laszlo Ujfalusi, Matteo Giordano, Ferenc Pittler, Tamas G. Kovcs, Imre Varga
Phys.Rev. D92 (2015) no.9, 094513, arXiv:1507.02162
Citations: 7 (independent: 4)

11. The running coupling of the minimal sextet composite Higgs model
Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong
JHEP 1509 2015 039, arXiv:1506.06599
Citations: 34 (independent: 23)

12. QCD thermodynamics with continuum extrapolated Wilson fermions II
Szabolcs Borsanyi, Stephan Durr, Zoltan Fodor, Christian Holbling, Sandor D. Katz, Stefan Krieg, Daniel Nogradi, Kalman K. Szabo, Balint C. Toth, Norbert Trombitas
Phys.Rev. D92 2015 1 014505, arXiv:1504.03676
Citations: 19 (independent: 16)

13. The running coupling of 8 flavors and 3 colors
Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong
JHEP 1506 2015 019, arXiv:1503.01132
Citations: 23 (independent: 15)

14. An Ising-Anderson model of localisation in high-temperature QCD
Matteo Giordano, Tamas G. Kovacs, Ferenc Pittler
JHEP 1504 (2015) 112, arXiv:1502.02532
Citations: 7 (independent: 2)

15. The lattice gradient flow at tree-level and its improvement
Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong
JHEP 1409 2014 018, arXiv:1406.0827
Citations: 49 (independent: 40)

16. Charmonium spectral functions from 2+1 flavour lattice QCD
Szabolcs Borsanyi, Stephan Durr, Zoltan Fodor, Christian Hoelbling, Sandor D. Katz, Stefan Krieg, Simon Mages, Daniel Nogradi, Attila Pasztor, Andreas Schafer, Kalman K. Szabo, Balint C. Toth, Norbert Trombitas
JHEP 1404 2014 132, arXiv:1401.5940
Citations: 26 (independent: 23)

3.2 Conference proceedings

17. The twelve-flavor β-function and dilaton tests of the sextet scalar
Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chik Him Wong
accepted to European Physical Journal, arXiv:1712.08594
Citations: 0 (independent: 0)

18. Spectroscopy of the BSM sextet model
Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chik Him Wong
accepted to European Physical Journal, arXiv:1711.05299
Citations: 0 (independent: 0)

19. A new method for the beta function in the chiral symmetry broken phase
Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chik Him Wong
accepted to European Physical Journal, arXiv:1711.04833
Citations: 1 (independent: 0)

20. Weakly coupled conformal gauge theories on the lattice
Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chik Him Wong
accepted to European Physical Journal, arXiv:1711.00130
Citations: 0 (independent: 0)

21. Pure SU(3) Topological Susceptibility at Finite Temperature with the Wilson Flow
Szabolcs Borsanyi, Zoltan Fodor, Sandor D. Katz, Simon Mages, Daniel Nogradi, Kalman K. Szabo
PoS LATTICE2015 2016 164
Citations: 0 (independent: 0)

22. Status of a minimal composite Higgs theory
Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong
PoS LATTICE2015 2016 219, arXiv:1605.08750
Citations: 16 (independent: 10)

23. New approach to the Dirac spectral density in lattice gauge theory applications
Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong
PoS LATTICE2015 2016 310, arXiv:1605.08091
Citations: 5 (independent: 3)

24. Running coupling of the sextet composite Higgs model
Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong
PoS LATTICE2015 2016 222, arXiv:1511.04890
Citations: 0 (independent: 0)

25. Toward the minimal realization of a light composite Higgs
Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong

PoS LATTICE2014 2015 244, arXiv:1502.00028
Citations: 25 (independent: 16)

26. Baryon spectrum in the composite sextet model
Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong
PoS LATTICE2014 2015 270, arXiv:1501.06607
Citations: 11 (independent: 7)

27. The lattice gradient flow at tree level
Daniel Nogradi, Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Chik Him Wong
PoS LATTICE2014 2014 328, arXiv:1410.8801
Citations: 7 (independent: 1)

28. The chiral transition as an Anderson transition
Matteo Giordano, Sandor D. Katz, Tamas G. Kovacs, Ferenc Pittler
PoS LATTICE2014 (2014) 214, arXiv:1410.8392
Citations: 6 (independent: 1)

29. Spectral functions of charmonium with 2+1 flavours of dynamical quarks
Szabolcs Borsanyi, Stephan Durr, Zoltan Fodor, Christian Hoelbling, Sandor D. Katz, Stefan Krieg, Simon Mages, Daniel Nogradi, Attila Pasztor, Andreas Schafer, Kalman K. Szabo, Balint C. Toth, Norbert Trombitas
PoS LATTICE2014 2015 218, arXiv:1410.7443
Citations: 3 (independent: 3)

30. QCD thermodynamics with dynamical overlap fermions
Balint C. Toth, Szabolcs Borsanyi, Ydalia Delgado, Stephan Durr, Zoltan Fodor, Sandor D. Katz, Stefan Krieg, Thomas Lippert, Daniel Nogradi, Kalman K. Szabo
PoS LATTICE2013 2014 163
Citations: 2 (independent: 1)

31. The chiral condensate from the Dirac spectrum in BSM gauge theories
Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chik Him Wong
PoS LATTICE2013 2014 089, arXiv:1402.6029
Citations: 10 (independent: 2)

32. Can a light Higgs impostor hide in composite gauge models?
Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chik Him Wong
PoS LATTICE2013 2014 062, arXiv:1401.2176
Citations: 48 (independent: 34)

33. Computational efficiency of staggered Wilson fermions: A first look
David H. Adams, Daniel Nogradi, Andrii Petrashyk, Christian Zielinski
PoS LATTICE2013 2014 353, arXiv:1312.3265
Citations: 4 (independent: 0)

4 Honors, awards and fellowships

I was honored by a number of awards which were directly connected to my work on the present research program.

- 2018 (expected, process started in 2017), Doctor of Academy (Hungarian Academy of Sciences)
- 2017 - 2018, visiting professor of excellence (Catedra de Excelencia, Universidad Autonoma, Madrid, Spain)
- 2017, Bolyai-plaquette (Hungarian Academy of Sciences)
- 2016, Rectoral Prize of Excellence (Eotvos Lorand University)
- 2015, ELTE Promising Researcher (Eotvos Lorand University)
- 2015, Karoly Novobatzky Prize (Eotvos Physical Society)
- 2013 - 2016, Janos Bolyai Research Fellowship (Hungarian Academy of Sciences), final qualification: excellent

5 BSc/MSc/PhD students

I have supervised a number of BSc/MSc/PhD students in lattice field theory while carrying out the work presented in this report.

- 2016 - present, PhD, Lorinc Szikszai, (Eotvos Lorand University)
- 2016 - present, MSc, Zoltan Varga, (Eotvos Lorand University)
- 2016 - 2017, BSc, Istvan Markusz, (Eotvos Lorand University)
- 2015 - 2016, MSc, Andras Saradi, (Eotvos Lorand University)
- 2015 - 2016, MSc, Lorinc Szikszai, (Eotvos Lorand University)
- 2015 - 2016, BSc, Marton Nemeth, (Eotvos Lorand University)
- 2015 - 2016, BSc, Istvan Vona, (Eotvos Lorand University)
- 2013 - 2014, BSc, Szikszai Lorinc, (Eotvos Lorand University)
- 2012 - 2013, PhD co-supervisor (PhD supervisor: David Adams), Christian Zielinski (Nanyang Technological University, Singapore)
- 2012 - 2013, BSc, Andras Saradi, (Eotvos Lorand University)
- 2012 - 2013, BSc, Zoltan Labszki, (Eotvos Lorand University)
- 2012 - 2013, BSc, Gabor Denes Oszkar, (Eotvos Lorand University)

6 Conferences, workshops, seminars

The members of my research group gave invited plenary talks, regular talks and seminars, participated at several conferences, workshops and schools where our work was presented.

6.1 Daniel Nogradi

- 2018, January 26, seminar, Wuppertal University, Wuppertal, Germany
- 2017, October 25, seminar, Universidad Autonoma de Madrid, Madrid, Spain
- 2017, June 18 - 24, The 35th International Symposium on Lattice Field Theory, Granada, Spain
- 2017, February 27, seminar, California State University Long Beach, Long Beach, USA
- 2016, December 14, seminar, Trinity College, Dublin, Ireland
- 2016, November 14, seminar, DESY, Berlin, Germany
- 2016, August 28 - September 4, XIIth Quark Confinement Conference, Thessaloniki, Greece
- 2016, August 1 - 3, XQCD Conference, Plymouth University, UK
- 2016, July 24 - 30, The 34th International Symposium on Lattice Field Theory, University of Southampton, UK
- 2016, April 4 - 15, Composite Dynamics, from Lattice to the LHC Run II, Mainz Institute for Theoretical Physics, Johannes Gutenberg University, Mainz, Germany
- 2015, October 30, seminar, MTA - Wigner Center, Budapest, Hungary
- 2015, August 1 - 28, Lattice Gauge Theory for the LHC and Beyond Program, Kavli Institute of Theoretical Physics, UCSB, Santa Barbara, USA
- 2015, July 14 - 18, The 33rd International Symposium on Lattice Field Theory, Kobe, Japan
- 2015, March 24 - 27, Bound states in QCD and beyond workshop, St Goar, Germany
- 2014, June 23 - 28, The 32nd International Symposium on Lattice Field Theory, Columbia University, New York, USA
- 2014, July 21 - August 1, Conceptual advances in lattice gauge theory workshop, CERN, Geneva, Switzerland
- 2013, August 6, Origin of Mass - Lattice BSM workshop, Odense, Denmark
- 2013, June 21, Pierrefest, Institute Lorentz, University of Leiden, Leiden, the Netherlands
- 2013, May 8, seminar, Eotvos University, Budapest, Hungary
- 2013, April 25, seminar, Higgs Center for Theoretical Physics, University of Edinburgh, Edinburgh, UK
- 2013, April 11, Ortvay Colloquim, Eotvos University, Budapest, Hungary
- 2013, April 8, seminar, CP3-Origins, University of Southern Denmark, Odense, Denmark

6.2 Santanu Mondal

- 2015, July 14 - 18, The 33rd International Symposium on Lattice Field Theory, Kobe, Japan
- 2015, February 16 - 20, Perspectives and Challenges in Lattice Gauge Theory Workshop, Tata Institute of Fundamental Research, Mumbai, India
- 2014, June 23 - 28, The 32nd International Symposium on Lattice Field Theory, Columbia University, New York, USA
- 2014, March 5 - 7, Lattice Practices Workshop, DESY, Zeuthen, Germany

6.3 Ferenc Pittler

- 2016, July 24 - 30, The 34th International Symposium on Lattice Field Theory, University of Southampton, UK
- 2015, November 25, seminar, Eotvos University, Budapest, Hungary
- 2014, October 8 - 10, Non-perturbativ Methods in Quantum Field Theory Workshop, Balatonfured, Hungary
- 2014, June 23 - 28, The 32nd International Symposium on Lattice Field Theory, Columbia University, New York, USA

6.4 Zsolt Szep

- 2017, September 20 - 22, Austrian-Croatian-Hungarian Triangle Meeting, Non-Perturbative Methods in Quantum Field Theory, Zalakaros, Hungary

6.5 Lorinc Szikszai

- 2018, January 8 - 26, GGI lectures on the theory of fundamental interactions, Galileo Galilei Institute for Theoretical Physics, Firenze, Italy
- 2017, February 6 - 10, Cracks and Blind Spots in the Standard Model, 9th Odense Winter School on Theoretical Physics, Odense, Denmark