PREFACE

This collection of papers is devoted to Dmitry Diakonov (1949–2012), Victor Petrov (1955–2021), and Maxim Polyakov (1966–2021)[1]. These three brilliant theorists are exemplary representatives of the Gribov school of theoretical physics, which thrived in St. Petersburg (Leningrad) in the second part of the 20$^{\mathrm{th}}$ century. The school originally emerged at the Theory Department of the Ioffe Institute (Leningrad Physical-Technical Institute at that time), which to a large extent was a cradle of all Soviet physics. The Ioffe Institute has a rich tradition of doing theoretical physics, it is sufficient to mention such names as Yakov Frenkel, Lev Landau, George Gamow, Matvey Bronstein, and Ilya Shmushkevich. In more recent times, Vladimir Naumovich Gribov was the undisputed leader of the Particle Theory Group, both formal and informal. In the beginning of the 1970s a research nuclear reactor was built in Gatchina near Saint Petersburg and the Ioffe Institute spun off all theoretical and experimental research in particle and nuclear physics to the newly organized Petersburg (Leningrad) Nuclear Physics Institute (PNPI) in Gatchina, about forty kilometers from the center of St. Petersburg.

The High Energy Theory Group at PNPI was at that time one of the leading world centers of research in high-energy particle physics. Especially flourished research on the Regge theory of scattering at high energies, results of the Gatchina theorists in this field were duly acknowledged by the worldwide theoretical community. The emphasis on the non-Lagrangian approach was due to Landau, Abrikosov, and Khalatnikov, who, in the mid-50s, discovered that QED has the zero charge and is therefore not a self-consistent theory. It seemed at that time that all field theories suffer from this disease, the argument was based on the sign of the polarization operator which followed from unitarity[2]. Somewhat paradoxically, Alexey Anselm, one of the prominent Gatchina theorists (and future advisor of Mitya Diakonov), at the beginning of his scientific career in the 50s discovered an asymptotically free two-dimensional quantum field theory[3] and even reported his results at the Landau seminar. However, senior theorists considered his results as a peculiarity of two-dimensional physics and did not pursue this direction of research. In the volume to the memory of Wolfgang Pauli, Landau famously wrote that “We are driven to the conclusion that the Hamiltonian method for strong interaction is dead and must be buried, although, of course, with deserved honor”.

[1] Mitya, Vitya, and Maxim, as they were known to their friends and colleagues.

[2] Much later it turned out that in non-Abelian theories there are contributions to the polarization operator without an imaginary part, thus avoiding this argument.

[3] Today, we call it the Neveu–Schwartz model.

Gribov was a disciple of Lev Landau, his apparent heir. He supported the traditions of the Landau school, its spirit of free discussion, where all participants, from graduate students to esteemed professors, took part without regard for their formal positions and titles. It was this Theory Department, which Mitya joined as an aspirant[4] after graduating from the St. Petersburg University at the beginning of the 70s.

The beginning of the 70s was an exciting time in particle physics. Asymptotic freedom was discovered, QCD and the Standard Model were formulated, experimental research on deep inelastic scattering was fast developing and, finally, during the November revolution of 1974, c-quark was discovered. Mitya joined the Department at this exciting time. After a few years working under the guidance of A.A. Anselm on the electroweak theory, he defended his Candidate of the Physical-Mathematical Sciences (Ph.D.) dissertation. At this time, he already became a mature theoretical physicist choosing the direction of his research independently. As was habitual in the Soviet system, he remained at the PNPI as a junior researcher[5]. After the Ph.D. defense, Mitya joined the Yuri Dokshitzer and Sergey Troyan (also junior PNPI researchers at the time) research program, and in a series of works, they developed theQCD theory of hard processes, which was summarized in a famous review paper in *Physics Reports* (the so-called DDT paper).

Next, he turned his attention to nonperturbative QCD problems. As a first step, he and one of us worked on the U(1) problem. The idea was to use the model-independent machinery of field theory and Ward identities to understand the reasons for the nonzero correlator of topological charge densities. This formal field-theory-based approach seemed to be unorthodox in the Department, where only recently, the field theory was considered hopelessly obsolete.

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[4] The Soviet educational system was different from the American one. In the Physics Department of the St. Petersburg (Leningrad) State University, the courses took five and a half years. In the last two–three years, a student usually had a scientific advisor and was supposed to prepare a diploma paper, roughly equivalent to the U.S. Master thesis. After the defense of the diploma, a student was issued a graduation certificate. A small proportion of graduates, who wanted to pursue a scientific career, usually were, on a competitive basis, accepted to aspirantura, either at the University they graduated from, or another University or a research institution of the Soviet Academy of Sciences. Aspirant was supposed to start doing research, initially under the guidance of a senior person. The aspirant was not obligated to take any more courses, except a foreign language (usually English) and philosophy.

[5] This position roughly corresponds to the American postdoc, but in the Soviet system, a junior researcher enjoyed much more independence and freedom in the choice of direction of his/her research than a typical postdoc.

The periodic structure of the QCD vacuum resembles the periodic potential in crystals and the authors discovered that for the solution of the U(1) problem, the potential barriers should be penetrable. In its turn this means existence of a massless ghost pole in a correlator of certain gauge noninvariant topological quantities, which leads at the end of the day to the emergence of mass of the η' boson even in the chiral limit[6]. All these considerations were model independent and used only general properties of QFT, what went even contrary to the spirit of the effective Lagrangian approach becoming popular at that time. Still, the authors yielded to the Zeitgeist and, under some plausible assumptions, derived an effective chiral Lagrangian integrating over quarks in the QCD Lagrangian.

These works inspired Mitya's interest in the mechanisms and nonperturbtive dynamics of strongly interacting theories, and he devoted all his following career to such research. Transitions between vacuum states with different topological quantum number, which were necessary for the solution of the U(1) problem, are realized by instantons, so Mitya started to consider instantons as excellent candidates for description of the low-energy QCD dynamics. He initiated an ambitious program of deriving numerous properties of low-lying hadrons from nonperturbative QCD dynamics based on instantons.

At the beginning of the 80s he joined forces with a newly minted, at that moment Ph.D. candidate, Victor Petrov. Victor was also a bright graduate of the Physics Department of the St. Petersburg University. After graduation, Victor initially worked on condensed matter theory problems at the Ioffe Institute, where he obtained a number of important results. Condensed matter experience was later of great help in Vitya's work on particle theory. But Vitya's first love was always particle theory and he soon became an aspirant at the Theory Department of PNPI. Two prominent theorists, Igor Tikhonovih Dyatlov and Gennady Stepanovich Danilov, became his advisors. They worked on the problems of vacuum structure, charge screening, and confinement in two-dimensional QED (the Schwinger model and its generalizations). These works formed the basis of Vitya's Ph.D. thesis, which he defended in December of 1984.

Still working on the Schwinger model, he joined forces with Mitya to work on nonperturbative QCD. Thus started a remarkable lifelong collaboration and friendship, which lasted a few decades and was terminated only with Mitya untimely passing away. Mitya's and Vitya's skills and approaches finely complemented each other. All their principal results are a fruit of their joint work and it is impossible, and not needed to separate their individual contributions to these achievements. Starting in the early 80s they devel-

[6] For more details, see the contributions of Victor Petrov, Michael Eides, and others in this volume.

oped a quantitative QCD-based theory of instanton vacuum, theory of chiral symmetry breaking and chiral condensates in this vacuum, chiral theory of nucleons, and so on, and so forth[7]. After the collapse of the Soviet Union, traveling abroad and unimpeded contacts with foreign physicists became possible, and Vitya and Mitya were joined in the work on the instanton vacuum by the group of Professor Klaus Goeke[8] in Bochum.

Mitya and Vitya worked a lot with graduate students, and two talented graduate students from St. Petersburg joined work on the instanton vacuum model, Pavel Pobylitsa at the end of the 1980s and Maxim Polyakov at the beginning of the 1990s.

Unlike the other two our heroes, Maxim was not a native of St. Petersburg. He came to St. Petersburg from the Siberian city of Irkutsk, with which he maintained personal and scientific contacts during all his life. Maxim graduated from the St. Petersburg University in 1989 with a Master degree and joined the PNPI aspirantura. He defended his Ph.D. dissertation in 1993. It was based on his work on the low-energy pion–nucleon interactions and theory, conducted in collaboration with Vladimir Vereshagin, Anatoly Bolokhov, Simon Sherman, and others. Besides working later under the guidance of Mitya and Vitya, and then collaborating with them for many years, Maxim Polyakov has to his credit a lot of independent work. He pretty soon developed into a mature and original researcher. Maxim made important contributions to the theory of hard processes, deeply virtual Compton scattering, generalized parton distributions, *etc.* Maxim was one of the pioneers, who renewed the interest and actively participated in the research on the hadron energy-momentum tensor, its properties, and its form factors. Later, together with Vitya and one of us, he developed a hadrocharmonium (not to mix with the quark-soliton model of Θ^+) approach to the relatively recently discovered heavy LHCb pentaquarks with hidden charm. He also continued to work on the soliton model for baryons, including exotica and heavy baryons.

With years it turned out that the QCD instanton vacuum model successfully describes properties of all low-energy hadrons with an accuracy about 10%. Besides successful description of already known features of low-energy hadron world, the instanton liquid model allowed to approach some prob-

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[7] See lists of their publications in Inspire-HEP and numerous contributions in this volume.

[8] Klaus Goeke, who prematurely passed away in 2011, was the leader of the hadron theory group in Bochum. When the borders between East and West opened in the early1990s, he managed to bring together many young people from different countries to collaborate on modern, nonperturbative aspects of QCD. Mitya, Vitya, Maxim, and many of the authors of this volume were frequent visitors and/or fellows at the Institute of Theoretical Physics II, and Maxim took up a professorship at Bochum University after Klaus Goeke's death.

lems, which were not accessible for the theoretical analysis by other methods: calculation of wave and structure functions of nucleons, nucleon–nucleon potential, pion–nucleon scattering, fraction of multiquark contributions in the nucleon wave function, *etc.*

Among numerous applications of the instanton liquid model, one stood apart and attracted a lot of attention in the high-energy physics community. This was a prediction a in a paper by Mitya, Vitya, and Maxim of a new exotic, narrow, relatively light five-quark state with definite mass. On Mitya Diakonov's suggestion, this state was later called Θ^+ [9]. The story of Θ^+ is full of dramatic twists and turns. Six years after the prediction was published, experimental results emerged, which seemed to confirm existence of Θ^+ with expected properties. Θ^+ was even included in the Particle Data Tables in 2003. A flood of experimental and theoretical papers on Θ^+ and a great excitement in the community followed. Not all theorists immediately agreed with the theoretical arguments in favor of Θ^+, but it seems that the theoretical objections were successfully rebuffed in the follow-up discussions and papers. However, the ultimate judge in physics is experiment, and later experiments with a larger statistics failed to confirm the discovery of Θ^+. The majority opinion at the time of this writing is against Θ^+, but we think that the final verdict is still pending[10].

Dmitri Diakonov, Victor Petrov, and Maxim Polyakov made original, innovative and well recognized by the community contributions to the development of high-energy theory. Many of their results will remain for a long time. Unfortunately, untimely deaths interrupted their productive work at the peak of their creative powers. This collection of papers is a small tribute to their achievements and their memory by some of their friends and colleagues.

The papers published in this volume fall into three different but not sharply distinguishable categories. At the beginning, we include the recollections of the authors who knew Mitya, Vitya, and Maxim well. Then we present scientific articles closely related to the topics that Mitya, Vitya, and Maxim worked on and developed. Finally, articles on several other topics by friends and acquaintances conclude this volume.

We begin with a moving lecture by Vitya Petrov delivered in 2014[11], at the XLVIII Petersburg Nuclear Physics Institute Winter School, given on the occasion of the would-be 65$^{\text{th}}$ anniversary of Mitya Diakonov, translated from Russian by one of the editors (M.E.). It reviews Mitya's scientific

[9] See Appendix to Igor Strakovsky's contribution in this volume.

[10] See the contributions of Michał Praszałowicz, Moskov Amaryan, Igor Strakovsky, and others in this volume.

[11] Note that this lecture commemorating Mitya Diakonov after his death in 2012 was given only 7 years before Vitya and Maxim passed away in 2021.

path and describes the results they obtained together, and also with Maxim. Next, Michael Eides recalls his friendship and long-standing collaboration with Mitya and Vitya, as well as Maxim, both from the perspective of their shared scientific interests and personal relationships against the background of historical events of the 1980s and 1990s. In the following articles, Michael Semenov-Tian-Shansky, Alexander V. Turbiner, and Edward Shuryak tell their stories about friendship with Mitya. Edward Shuryak also recalls Mitya's scientific career and his scientific interests. Mirzayusuf Musakhanov in his memoirs recalls Mitya and also Vitya and Maxim highlighting their pioneering works on the instanton vacuum and their ability to collaborate with scientists from different institutes and countries, like Bochum in Germany or Busan and Incheon in Korea.

The hallmark of Mitya, Vitya, and Maxim work is undoubtedly the instanton model of the QCD vacuum and the resulting chiral model for baryons. Christian Weiss in his article reviews the instanton vacuum model and its recent applications to the gluonic QCD operators. As already mentioned above, the prediction of the low-mass and even more importantly, small-width exotic pentaquark following from the instanton liquid model, has attracted much attention in the high-energy physics community. The pentaquark paper by Mitya, Vitya, and Maxim was published in 1997, however, the first positive experimental results appeared only in 2003. In a letter to Anatoly Dolgolenko, the leader of the ITEP experimental group claiming to have observed Θ^+, Mitya included his interview for the Russian magazine *Atomium*, in which we can find his thoughts on the subject at that time. Here, we present a translation of this historical email.

Michał Praszałowicz in his article reviews chiral models predictions for Θ^+ and some experimental evidence. More on the experimental situation can be found in the next paper by Moskov Amaryan. Further theoretical and phenomenological details of light exotica are discussed by Hyun-Chul Kim who describes his long-lasting collaboration with Maxim, and also by Atsushi Hosaka who recalls his meetings and discussions with Mitya.

The existence of Θ^+ implies the decuplet of light pentaquarks, among them, the nucleon-like states. It was Maxim who was the first one to understand that the photoexcitation of the nucleonic member of antidecuplet is favored for the neutron and suppressed for the proton, which has been observed in various experiments. Igor Strakovsky describes experimental evidence for this narrow nucleonic pentaquark $N^*(1680)$, in particular the partial wave analysis he was involved in.

The future experimental searches for Θ^+ already mentioned by Moskov Amaryan, are in more detail discussed in the papers by Takashi Nakano (who supervised the first positive analysis discovering Θ^+ at the SPring-8 facility) and collaborators, by Byung-Geel Yu, Kook-Jin Kong, and Tae Keun Choi, and also by Jung Keun Ahn.

Changing the subject, Eberhardt Klempt in his paper discusses the parallels between the approach to the QCD confinement developed by Mitya and Vitya and the approach based on the so-called AdS/CFT correspondence.

The next three articles are closely related to Maxim's recent scientific interests, namely gravitational form factors. Cédric Lorcé and Peter Schweitzer discuss in general the energy-momentum tensor form factor $D(t)$ of hadrons in terms of pressure and shear force distributions, while Enrique Ruiz Arriola and Wojciech Broniowski concentrate in their paper on the pion. In the following article, Julia Panteleeva, Evgeny Epelbaum, Ashot Gasparyan, and Jambul Gegelia discuss gravitational form factors of the deuteron.

Finally, the last five papers are not directly related to the topics that Mitya, Vitya, and Maxim were directly involved in. Ian Balitsky recalls his encounters with Mitya and Vitya, and then presents his original research on the background field method and QCD factorization. Nikolay Kivel, after recalling the beginning of his scientific career and his relations with Mitya, Vitya, and Maxim, discusses particular processes where perturbative QCD is at work, namely, the two-photon exchange corrections at large momentum transfer. Mark Strikman and Leonid Frankfurt contributed two papers to this volume. In the first one, they review the history and progress in the studies of nucleon correlations in nuclei, and the second one is devoted to factorization in hard coherent processes. Finally, we conclude with a contribution by Alexander Gorsky, Arseniy Pikalov, and Arkady Vainshtein, where they study the instability of ground states in certain field theoretical models in the large-N limit.

We hope and believe that this collection of articles reflects the scientific achievements of Dmitry Diakonov, Victor Petrov, and Maxim Polyakov, and their place on the international scene of theoretical particle and nuclear physics. We would like to thank all contributors for their enthusiasm and support for this project and for making this special volume a reality. It took several years to fully appreciate what a loss the untimely death of our friends was. A loss for science, for institutions they worked in, but also a personal loss for their friends and relatives. And although they are not among us, they are alive in their works and live in our memory.

Michael Eides
Michał Praszałowicz
Igor Strakovsky