Complex Dynamics and the Future of Particle Physics

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Abstract

In this report we argue that complex dynamics has the potential of becoming a key tool for the "new physics" sector of particle theory. The report includes a list of candidate signals for "new physics" that were recently recorded above the scale of electroweak interaction. Some of the pioneering efforts directed towards application of complex dynamics in high-energy physics are briefly surveyed.

Keywords: Dynamics and non-equilibrium phase transitions; dynamics of disordered systems; quantum dynamics and non-equilibrium statistical mechanics; strange attractors and chaotic dynamics

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Biographical Notes: E. Goldfain is a Senior Research and Development Scientist with Welch Allyn Inc., Photonics Center of Excellence, located in New York State, USA. He has received 13 patents on optical systems for biomedical applications and has published 28 contributions in ISI-listed journals with a total citation numbers of 114 and an H-index of 7. Several instruments based on his designs have been honored with prestigious Research and Development awards. His interests include novel Photonics technologies and advanced research in High-Energy Physics (Quantum Field Theory, Nonlinear Science and Complexity Theory, Quantum Optics).

1. Introduction

The standard model (SM) is a highly successful theoretical framework that combines in a fundamental way three generations of quarks and leptons with three varieties of gauge forces [1]. It has been laboriously built and tested over the years using large datasets gathered at particle colliders around the world. Despite its remarkable explanatory power, SM leaves many questions unanswered. These questions fall into three broad groups. The first revolves around phenomena that are not described by SM, such as classical gravitation, dark matter, dark energy, baryogenesis and inflation. The second question targets the origin of electroweak symmetry breaking (EWSB): what physical mechanism breaks the symmetry between photon (γ) and the gauge bosons of weak interaction ($W^{\pm}$ and Z^0)? The final group of questions boils down to "What determines the structure of SM?" Particularly, SM remains silent on why the forces and interaction strengths are the ones we observe, why the quarks and leptons have the masses they do, and why no other gauge forces and matter particles are allowed below the scale of electroweak interaction. In addition, SM does not account for neutrino oscillations and masses and is unable to explain why only fermions with one handedness experience the force transmitted by massive gauge bosons.

2. Candidate Signals for Physics beyond SM

In addition to the open questions listed above, a series of anomalous observations have recently surfaced from both collider and astrophysical measurements. These results point in the same direction, namely that current models have limited ability to explain phenomena above few hundred GeV. Since some of the data are preliminary, it is premature to conclude that what we are seeing are definitive signals for physics beyond SM. However, one may reasonably suspect that a revision of current conceptual paradigms might be called for when it comes to physics unfolding above the electroweak scale or reaching the TeV threshold. A list of partially confirmed observations contains the following items:
1) Measurement of anomalous couplings in scattering of longitudinal gauge bosons at large transverse momentum [2]. 2) Detection of ultra-heavy gauge bosons (Z') at 240 and 720 GeV marks of the mass distribution [2]. 3) Excessive numbers of positrons detected by PAMELA and muons by CDF [3, 4].
4) Observation of the fourth family quark [5]. 5) Measurement of a strong phase in the study of B-s mesons [2]. 6) Measurement of photon time delay in gamma rays using FERMI Large Area Telescope [6].

3. Why is Complex Dynamics Relevant to High-energy Physics?

We briefly review here the rationale for including complex dynamics in extensions of particle physics beyond SM:

a) It is known that SM is founded on the principles of relativistic quantum field theory (QFT), a robust synthesis of quantum mechanics and special theory of relativity. QFT is defined via a set of nonlinearly interacting fields and a number of parameters generically called "coupling constants". By construction, QFT represents a replica of *equilibrium* statistical physics, as embodied in the apparatus of Boltzmann-Gibbs (BG) distributions. These distributions describe the long-term behavior of underlying fields. On ultra short time scales, the action of unstable and persistent quantum corrections is likely to violate the equilibrium ansatz and set the stage for *non-equilibrium* dynamics. In contrast to equilibrium conditions, non-equilibrium enables manifestation of chaos and complex behavior in QFT, with a strikingly rich spectrum of possible outcomes [7, 8].

b) It is also known that the Renormalization Group (RG) is a powerful method for the study of QFT under *scaling* transformations [1, 9]. Using the observation scale as an independent evolution parameter, RG equations describe the trajectories of fields and coupling constants towards or away from a functional attractor set. When applied to SM, it is customary to consider that the fields under study and random fluctuations acting on them are *separable* entities. This enables all fluctuations to be integrated out one at a time and reabsorbed in a re-definition of coupling constants. The presence of large and unsuppressed quantum corrections emerging on ultra short time scales can lead to a violation of this basic assumption. Fluctuations and fields can become strongly coupled, RG trajectories are no longer smooth and regular, attractors loose stability against perturbations and morph into sets displaying complex structure [10, 11].

Although a universal definition of *complex dynamics* and *complex systems* is lacking, their main attributes may be summarized as follows [12]:

a) Complex systems are open ensembles of many constituents interacting nonlinearly.

b) A complex system possesses a structure spanning several scales.

c) A complex system is capable of self-organization and emerging behavior.

d) Complex dynamics involves an interplay between order and chaos.

e) Complex dynamics involves an interplay between cooperation and competition.

The above considerations show that ultra-short time intervals prevent thermalization and create an environment favoring the onset of complex dynamics. In this type of setting, the underlying principles of classical statistical physics and traditional QFT are likely to break down. In particular the ergodic theorem, the fluctuation-dissipation theorem, analyticity, unitarity, locality, finiteness in all orders of perturbation theory and renormalizability are either violated or loose their conventional meaning and require revision [13 and included references].

4. Recent Developments and Future Challenges

In the last decade, the number of studies linking complex dynamics to quantum field theory and high energy physics has been growing at a fast pace. Due to the vast number of contributions on this topic, a survey of relevant papers is impractical and falls outside the scope of this report. As of today, several trends set the main direction of research. Among them we mention use of methods related to the Cantorian structure of space-time in the ultraviolet sector of quantum physics, use of fractional dynamics and non-extensive statistical mechanics beyond SM, use of universal approach to chaotic dynamics, spatio-temporal chaos and pattern formation to clarify some of the open questions raised by SM, methods related to stochastic quantization and coupled map lattices. The reader is referred to [14-16] for guidance and additional details.

As with all pioneering efforts in science, there is a host of challenges lying ahead insofar as integration of complex dynamics in high-energy physics is concerned. For example, one needs to understand if non-equilibrium dynamics is still driven by the fundamental principles of least action and invariance under unitary groups of transformation [1, 9]. If systems slightly out of equilibrium can be adequately modeled from such principles, than it is likely that employing fractional Euler-Lagrange formalism, fractional Noether theorem and generalized symmetry groups provide a sound baseline [17]. If, on the other hand, far-from-equilibrium systems do not follow such principles, novel modeling tools related to collective behavior in large networks of nonlinear oscillators, complex Ginzburg-Landau equation, Fokker-Planck equation, reaction-diffusion equations and their fractional or vectorial extensions will take center stage in this development program.

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