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The Future of Theoreticle Particle Physics: A Summary

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Abstract

From history, it can be traced that fundamental physics began the twentieth century with the revolution of two great important theories in physics namely: relativity and quantum mechanics. On one hand, a good number of years of the second half of the century was devoted to the construction of a theoretical structure with a view of unifying these radical ideas. On the other hand, this foundation has also led us to a number of paradoxes in our understanding of nature. Many attempts to make sense of quantum mechanics and gravity at the smallest distance scales lead inexorably to the conclusion that space-time is an approximate notion that must emerge from more primitive building blocks. Furthermore, violent short-distance quantum fluctuations in the vacuum seem to make the existence of a macroscopic world wildly implausible, and yet we live comfortably in a huge universe. Now, what, if anything, tames these fluctuations? Why is there a macroscopic universe? These are two of the central theoretical challenges of fundamental physics in the twenty-first century. In this summary, we describe the circle of ideas surrounding these questions, as well as some of the theoretical and experimental fronts on which they are being attacked and predict what the future holds for theoretical particle physics.

Keywords: Relativity; Quantum mechanics; Standard model

Introduction

Practically all experimental data from high energy experiments can be accounted for by the so-called Standard Model (SM) of particles and their interactions, formulated in the 1970s [1]. Theoretical physics has played a crucial role in particle physics since its earliest days. Interpretation and synthesis of a broad range of experimental results (phenomenology), progress in quantum field theory, recognition of the role of symmetries, and invention of new calculational methods (perturbative techniques and lattice QCD) were all crucial in developing the SM. The SM also contains twenty-four fundamental particles (12 particles and their associated anti-particles), which are the constituents of all matter [2].

A major goal of physics is to find the 'common ground' that would unite all theories into one integrated theory of everything, of which all the other known laws would be special cases, and from which the behavior of all matter and energy could be derived at least in principle [3].

Following the convention of particle physicists, the term 'elementary particles' is applied to those particles that are, according to current understanding, presumed to be indivisible and not composed of other particles [4]. Particle Physics focuses on exploring tools necessary for attacking fundamental questions such as:

1. What is everything made out of?
2. How do the particles interact with each other?
3. What principles underlie the answers to these questions?
4. How can we use this information to predict and interpret the results of future experiments?

All particles and their interactions observed to date can be described almost entirely by a quantum field theory called the SM [5]. The SM of particle physics proposes some answers to these questions. Although it is highly doubtful that the SM will survive intact beyond this decade of more advancements in both theoretical and experimental physics, it is the benchmark against which future theories will be compared. Modern particle physics generally investigates the SM and its various possible extensions [6].

Theorists have been the drivers in asking the questions which lead beyond the SM. These include: the origin of the hierarchy between the scales of the weak and gravitational interactions, the physics of flavor, the origin of neutrino masses, the particle nature of dark matter, inflationary cosmology, baryogenesis, resolving the tension between quantum mechanics and gravity, and identification and explanation of dark energy.

The SM may be likely complete, in the sense that it is a consistent theory up to very high energies. It is now the background to all experimental explorations. There are many questions beyond the SM, and the field now confronts new and serious challenges. This is because in going beyond the SM, we are entering an environment with both high potential rewards and high risks.

Theorists have continued to propose possible new phenomena relevant to all three frontiers (Energy, Intensity and Cosmic) which will help guide future experimental studies and will respond to them. They will extend the structures of quantum field theory and quantum gravity, providing clues as to the possible underlying laws of nature, and they will continue to propose explanations for the hierarchy of energy scales, the origin of dark matter and similar mysteries, with implications for existing and proposed experiments. As they have for decades, they will provide critical input to analysis of experimental data.

Particle Physics Today

From theory and experiments, there are several arguments to believe that the SM is just the low energy limit of a more fundamental theory [7]. This is not necessarily true because the SM has been successfully tested at an impressive level of accuracy and provides at present our best fundamental understanding of the phenomenology of particle physics.The past five years have seen a major triumph of theoretical and experimental physics working hand in hand. The SM predicted the existence of a type of boson known as the Higgs boson. Early in the morning on 4 July 2012, physicists with the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) announced they had found a new particle that behaves similarly to what is expected from the Higgs boson [8].

This is an extraordinary experimental accomplishment. Nevertheless, this success also rests on theorists exquisite understanding of Quantum Chromodynamics (QCD), and ability to predict, for the simplest Higgs theory, the production rate and the decay branching ratios with great precision.

Early indications are that this particle is in fact the Higgs predicted by the simplest version of the SM, where simple has a precise meaning. This is the minimal number of degrees of freedom consistent with the symmetries of the strong, weak, and electromagnetic interactions, and the principles of quantum mechanics, locality, and special relativity.

Theorists have played and are still playing an important role in upcoming tests of the SM interpretation of the Higgs boson. Not only are they providing the required SM calculations for production and decay rates, new ways to test the properties of the Higgs boson, and alternative models against which these measurements can be tested, but they have a framework in which to quantify any would-be discrepancies between the simplest Higgs theory and experiment using the methods of 'effective field theory'.

On a slightly longer time scale, we have seen, over the the past two decades, many other successes of the SM. Among the most striking in recent years has been the experimental verification that the Cabbibo-Kobayashi Maskawa (CKM) phase explains the observed Charge-Parity (CP) violation in the K and B meson systems. This is a triumph for the SM and for experimental ingenuity.

However, it also reflects the development, over the past three decades, of a spectrum of theoretical tools, including: the general framework for weak interaction phenomenology employing the operator product expansion, the recognition of the incisiveness of time-dependent CP asymmetries, novel methods for understanding heavy quark systems, and an extraordinary increase in the ability to compute real physical quantities from lattice gauge theory.

Indeed, the progress in lattice gauge theory over the past decade has been astounding, including, for example, calculations of the hadron spectrum yielding precision measurements of light quark masses and computation of decay amplitudes necessary for the precise extraction of CKM parameters from data.

Another success for theory together with experiment has been the verification of SM predictions with amazing precision in collider experiments. Experiments at the Large Electron-Positron Collider (LEP) and Stanford Linear Collider confirmed the electroweak couplings with great accuracy and tested QCD in a clean environment.

This knowledge, together with improvements in the theory of hadron collider processes, has enabled SM tests and measurements at the Tevatron and the LHC with a precision that was unthinkable even a decade ago. The W mass measurement at the Tevatron, and the tests of the SM electroweak vector boson production rates and kinematic distributions, as well as the top quark pair-production cross sections at the Tevatron and the LHC, are just a few examples of this progress.

The past decade has also seen confirmation of the existence of neutrino masses and the measurement of neutrino oscillation parameters. Theorists have played an important role in every aspect of these developments. They first laid the theoretical foundation for understanding neutrino oscillations, in vacuum and including matter effects, and provided natural frameworks for explaining the extremely small values of the neutrino masses. Theorists also provided a detailed understanding of issues arising in the detection of these phenomena using neutrinos from the Sun, the atmosphere, nuclear reactors, and accelerators.

Prospects for Advances in Theory

In this section we consider five broad areas which include: phenomenology, field theory calculational methods, model building, astrophysics and cosmology, and string theory, quantum gravity and foundational questions. These are broad topics; within phenomenology, for example, we consider collider phenomenology, electroweak physics, neutrino physics, heavy quark physics and additional topics; in field theory, we include lattice gauge theory as well as perturbative and semiclassical methods; model building includes models of flavor, supersymmetry, grand unified theories (GUTs), and large or warped dimensions.

Phenomenology

The idea that all matter is composed of elementary particles dates from at least the 6th century BC [9]. Particle phenomenology plays a crucial role of linking experiments with the various aspects of theory, including model building, perturbative and lattice QCD, and more foundational issues. Over the past decades it has been central to the extraction of the parameters of the fundamental Lagrangian from experimental data. It played a vital role in the success of the Tevatron and LHC programs, leading to precision determination of the top quark properties and the discovery of the Higgs boson.

Many-body systems exhibit emergent phenomena that are not in any meaningful sense encoded in the laws that govern their constituents [10]. The phenomenology community has proposed many new kinematic variables now used on a daily basis by researchers in the LHC collaborations. In particular, theorists working on dark matter have proposed that the proper framework of analyzing direct detection experiments is in terms of the couplings of a low-energy effective theory, broadening the possible interpretations of these experiments. Phenomenology will remain critical to the interpretation of continuing and upcoming experiments and for developing plans for the future.

Flavor physics

The study of flavor physics was an integral part of the development of the SM. Theory has played a crucial role here, beginning with the idea of three generations of quarks, to heavy quark effective field theory and lattice QCD, which provided important form factors with a few percent uncertainty.

Proposals for physics beyond the SM are strongly constrained by flavor physics, whether or not they address directly the big questions of the subject.

Neutrino physics

In June of 1998 a very important event in neutrino physics occurred. The Super-Kamiokande collaboration reported a strong evidence for neutrino oscillations in their atmospheric neutrino data [11]. This was not a thunderstorm in a clear sky: the evidence for oscillating neutrinos has been mounting during the last two decades in the solar neutrino experiments [12], and previous data on atmospheric neutrinos also gave indications in favour of neutrino oscillations [13].

Neutrino theory sits at the intersection of particle physics, nuclear physics, astrophysics and cosmology, and as such provides great opportunities and interesting challenges. The experimental neutrino physics program has had tremendous success over the past fifteen years, beginning with the discovery of neutrino oscillations in solar and atmospheric neutrinos. Theory has played an important role in each step of these developments, from the calculation of neutrino fluxes from the Sun and from the atmosphere, to the recognition of the importance of matter effects.

This has focused the field on measurement and understanding of the neutrino masses and mixings, as well as fundamental issues such as whether neutrinos are their own anti-particles, the scales of neutrino mass generation, and the possible role of neutrinos in the creation of the asymmetry between matter and antimatter (leptogenesis).

There are also very wide discussions of possible next generation long baseline experiments with muon storage rings [14]. All these experiments are designed to probe a wide range of the neutrino mass squared differences and lepton mixing angles, and possibly Charge Parity (CP) violating effects in neutrino oscillations. They may also be able to test the fascinating possibility of matter enhancement of neutrino oscillations – the MSW effect [15].

Field theory calculational methods

In a variety of circumstances, it is possible to extract important results from experiment only through very precise theoretical predictions.

Perturbative and effective field theory methods: Nuclear forces have been studied in depth over the past fifty years, leading to excellent phenomenological descriptions [16]. A main goal of this enterprise has been to arrive at the “best” two-nucleon potential and to use it in many-body calculations to determine the properties of nuclear matter and finite nuclei. Effective field theory (EFT) analyses [17] offer a different perspective: There is no best two-body potential. Indeed, the off-shell behavior of a potential or amplitude is not observable and should not influence the predictability of the theory if a consistent power-counting scheme is used [18].

A more precise understanding of the physics of heavy hadrons has been enabled by several breakthroughs. First, the operator product expansion for weak transitions, and later, the successive development of heavy quark effective theory, nonrelativistic QCD, and most recently, soft collinear effective theory (SCET). These developments all represent the construction of effective field theories (EFTs) that arise from a separation of physical scales. They have had great practical payoff for the experimental study of B mesons, charmonia, and bottomonia.

There has also been enormous progress in computing cross sections relevant to both backgrounds and signals at colliders, at higher order in the strong coupling constants, and even including electroweak corrections.

One also cannot overstate the importance of precision electroweak theory. The triumph of precision electroweak measurements in predicting the Higgs mass would not have come about if the quantum corrections to the weak mixing angle and weak boson masses had not been known to two loop order.

Despite all this progress in precision applications of continuum quantum field theory, there is still plenty of room for new theoretical developments, both those with practical applications to experiments, and those that enlarge our understanding of quantum field theory and of the structure of physical law.

Lattice QCD: Lattice QCD is our main tool for understanding non-perturbative aspects of QCD. Numerical evaluation of hadronic matrix elements is crucial to progress in many areas of particle physics. The last decade has witnessed an enormous increase in the power of lattice methods. Lattice QCD has enabled the computation of weak matrix elements at the percent level, along with precise determination of the QCD couplings and the quark masses. Computations of the decay constants of the D and Ds mesons provide striking examples of recent progress.

Model building

In particle physics, the term model building refers to a construction of new quantum field theories beyond the SM that have certain features making them attractive theoretically or for possible observations in the near future. A model builder typically chooses new quantum fields and their new interactions, attempting to make their combination realistic, testable and physically interesting. In particular, an interesting new model should address questions left unanswered in the Standard Model.

TeV-scale model building: For TeV model building, the idea of supersymmetry, which can potentially resolve the hierarchy problem, has been an important driver of experiments. Supersymmetry predicts an array of new particles, often with properties which are a prior known, and this has led to a variety of experimental searches looking directly for these new particles.

Many of the searches for dark matter via direct detection have focused on the lightest supersymmetric particle, which is a natural candidate for dark matter. Models of leptogenesis provide a very strong motivation to map out the parameters of the neutrino sector in great detail, especially the CP properties.

In the LHC era, in which trigger bandwidth is critical and backgrounds are large, it is important to have models that cover as many signatures as possible. Split supersymmetry suggests quasi-stable gluons and leads to searches for out-of-time decays. Other models lead to quasi-stable charged particles or displaced vertices.

Having a large number of exotic models significantly expands the range of search strategies at the LHC experiments, reducing the likelihood of missing critical signals of new phenomena.

Flavor model building: The origin of the quark, lepton, and in recent years the neutrino mass matrices are among the great mysteries in particle theories. Theorists have explored a variety of ideas for understanding the hierarchies observed in the quark and charged lepton mass matrices. These have included, but are hardly limited to, flavor symmetries with small breakings, warped and extra dimension models, and composite and Technicolor models.

Grand unified theories: Grand unified theories (GUTs) are proposals to unify the strong, weak, and electromagnetic interactions into a single force. The quantitative unification of the three SM gauge couplings at the energy scale MG is one of the cornerstones of the GUTs paradigm. It is obviously of direct phenomenological relevance. Gauge coupling unification is best understood in the framework of effective field theory (EFT) [19]. They also unify quarks, leptons, anti-quarks and anti-leptons of each family into common multiplets. Such an arrangement would explain the coexistence of quarks with leptons, their quantum numbers, and the quantization of electric charge.

This unification is the principal direct evidence for GUTs. But the study of these theories has had other impacts. GUTs stimulated proton decay experiments, which helped solve the solar neutrino problem, and led to the discovery of atmospheric neutrino oscillations, and to the detection of neutrinos from a supernova.

String theory model building: There are many challenges in connecting string theory to the real world, but consideration of string models has profoundly influenced ideas for particle physics models. Some of these ideas include an understanding of light Higgs bosons, theorems demonstrating the absence of continuous global symmetries, the role of discrete symmetries, ideas for the origin of repetitive generations, a natural setting for the Peccei-Quinn solution of the strong CP problem, candidate fields and mechanisms for inflationary cosmology.

We anticipate further progress in this field, exploiting theoretical developments and responding to experimental discoveries and exclusions.

Astroparticle physics and cosmology

The combination of a cosmological constant with a distribution of cold dark matter particles after an initial period of inflationary expansion is now considered the SM of cosmology. This model has provided a simple explanation of diverse physical phenomena in the Universe.

However, even if this simple picture continues to be borne out, there is much still to explain, including the reason the cosmological constant has the value it does, the origin of cosmological density perturbations, and the nature of dark matter. Theorists have proposed a range of dark matter candidates.

Astrophysical and cosmological theory also plays a key role in the interpretation of a wide variety of current and future measurements, including dark matter experiments, massive galaxy surveys, gravitational lensing observations, and cosmic microwave background data.

The hypothesis of inflation came from particle theory, emerging from ideas about grand unification and monopoles. It is now a central part of the Cosmic Frontier and of the Theory program.

String theory, quantum gravity and foundational questions

The SM developed, in significant part, from theorists delving into fundamental questions in field theory. These included the demands of renormalizability and unitarity and the related constraint of freedom from anomalies. Its development and full understanding required that theorists master previously unfamiliar topics in mathematics such as group theory, topology and the theory of fiber bundles.

String theory grew out of efforts to understand the phenomenology of the strong interactions, and later blossomed into a unified approach to quantum mechanics and gravity. In particular, the resurgence of interest in string theory in 1984 followed the discovery of anomaly-free string theories that could incorporate the chiral gauge structure of the SM. Since then string theory has been a major source of new ideas in particle physics. It has provided insights into questions of unification, the strong CP problem, black hole physics, supersymmetry, the possibility of flat and warped extra dimensions, and much more. It has had an important indirect impact on particle physics by inspiring new computational approaches to ordinary perturbation theory.

As a theory of quantum gravity, string theory also has close ties to general relativity and there has been a fruitful interplay between string-theoretic methods and more conventional methods in the study of the properties of black holes. Supersymmetry, alone and in conjunction with techniques developed in string theory, continues to be a powerful tool for unraveling the dynamics of strongly-interacting gauge theories.

It should be noted that the black hole puzzles largely drove the discovery of gauge or gravity duality, forcing theorists to understand better the relation between the dynamics of black branes and D-branes. It seems that these puzzles continue will to be a fruitful source of insight and new ideas [20].

String theory practitioners have also contributed to advances in our understanding of cosmology, models of flavor physics, and much more. String theory and supersymmetry have also had a broad impact in pure mathematics in areas ranging from algebraic geometry to number theory. It is likely that the ideas and techniques to which string theory has led will be critical to resolving many of the questions we have about nature at the deepest level.

Practical application of particle physics

In principle , all physics and practical applications developed therefrom, can be derived from the study of fundamental particles. In practice, even if ‘particle physics’ is taken to mean only ‘high-energy atom smashers’, many technologies have been developed during these pioneering investigations that later find wide uses in society. Particle accelerators are used to produce medical isotopes for research and treatment, for example, isotopes used in Positron Emission Tomography (PET) imaging, or used directly in external beam radiotherapy.

The development of superconductors has been pushed forward by their use in particle physics. The world wide web and touchscreen technology were initially developed by CERN.

Additional applications are found in medicine, national security, industry, computing, science, and workforce development, illustrating a long and growing list of beneficial practical application with contributions from particle physics.

What does the future look like?

Theorists' seemingly complete understanding of physics, down to distance scales of order 10−17 centimeters, has brought other questions about the laws of nature into sharp focus. Again, theory plays a crucial role in delineating the questions and in suggesting possible answers. Among the questions which theorists have helped to identify and sharpen are:

What is the origin of the great disparity in the energy scales associated with the weak and gravitational forces? This is the hierarchy problem. It has two pieces: (1) why is there such a large disparity and (2) the problem of fine tuning such that any new energy threshold much above the masses of the W and Z bosons, such as the Planck scale or unification scale, tends to destabilize the Higgs boson mass through quantum corrections.

1. Where do the parameters of the SM originate?
2. Do the strong and electroweak forces unify at some energy scale?
3. Why is the strong interaction CP conserving? Is this accounted for by an axion field, and does this axion constitute some or all of the dark matter?
4. The quarks and leptons present many mysteries. Why are there repetitive generations? What accounts for the hierarchical structure of the masses and mixings of the quarks and charged leptons?
5. The discovery of neutrino mass has raised new questions. What is the energy scale associated with the generation of neutrino mass? Are neutrinos their own anti-particles?
6. The observed CP violation in the SM is insufficient to account for the baryon asymmetry of the Universe. What phenomena might account for this? Might they be accessible to experiments at the Energy or Intensity Frontiers?
7. What is the identity of the dark matter? What is its origin? Why is it just becoming important at the present epoch of the Universe?
8. What caused the inflationary epoch, and how did the Universe end up in its current state?
9. What is the nature of the quantum theory of gravitation?
10. From what set of principles or structures do the laws of nature originate?

Theorists are vigorously considering all of these questions. Some of them point to particular energy scales and types of experiments.

Experimentalists must explore all avenues, and theorists should follow their own instincts. Other speakers will talk about the ongoing program to connect string vacua to observation. But for me there is a clear challenge: to complete string theory, the same way that Einstein finished GR, using the kind of tools that have brought us to our current understanding. Obviously it will take longer, it has the quantum as well as the relativity. It may require concepts that we do not yet suspect. But we will succeed. This subject is currently in an exciting state, with new ideas from quantum information theory and the black hole information problem [21,22].

Proposals for physics beyond the SM include: Supersymmetry, a possible new symmetry of nature relating fermions and bosons, to understand the hierarchy between the Planck scale and the weak scale. In many realizations that theorists have considered, one might have expected its discovery in the first run at the LHC. Still, it remains one of the more plausible explanations, and is the subject of continued experimental and theoretical study.

On the other hand, Composite Higgs models, technicolor, and Randall-Sundrum models provide alternative possible explanations of the hierarchy problem, and are the subject of ongoing experimental searches.

Over the aspect of dark matter candidates where weakly interacting massive particles (WIMPs) are natural in supersymmetry and several other theoretical structures, axions ere invented to understand the strong CP problem. These are both topics of ongoing theoretical work and extensive experimental searches [23-26].

String theory in particular provides a promising model for the unification of gravity and the other forces in a consistent quantum mechanical framework. It has also provided new tools for addressing problems in quantum field theory and in disparate areas of physics including heavy ion physics and condensed matter physics. It has suggested new principles (holography) and inspired ideas for particle phenomenology and physics beyond the SM.

It has also inspired the invention of powerful techniques for computing scattering amplitudes.

Leptogenesis, on the other hand, is an attractive paradigm for explaining the baryon asymmetry of the Universe, which has an intimate connection with the origin of neutrino masses. Plausible indirect evidence for this mechanism would be the discovery of CP violation in the neutrino sector, the subject of tests in forthcoming long-baseline experiments. Other ideas for baryogenesis have different potential consequences.

In addition to raising questions, theorists have developped powerful perturbative and non-perturbative techniques for performing calculations essential for understanding collider experiments. Theoretical precision that was previously viewed as impossible is now routine. This precision has been, and will remain, crucial in both understanding SM physics and uncovering evidence of physics beyond the SM. This includes understanding

Tevatron and LHC data, as well as results from Beijing Electron Spectrometer (BES) III and Belle-II.

Upcoming results from the LHC or from experiments at any of the frontiers in the next decade might provide answers to some of these questions. For example, the hierarchy or ‘naturalness’ problem provides the principal argument that new physics should appear at the TeV-scale, and it has inspired a range of proposals for physics beyond the SM. Many specific proposals for new physics at the TeV-scale have been severely constrained by LHC searches, and the paradigm of naturalness has come under increasing scrutiny. However, there remains significant space to explore.

Answering theoretical questions will require experiments across the Frontiers. Intensity Frontier experiments and precision measurements at the Energy Frontier may provide evidence for new physics at slightly higher energy scales. Cosmic Frontier experiments may yield a WIMP candidate or further constrain this paradigm.

For other questions, experimental input is likely to be limited for a long while, and theorists will try to put together answers, at first tentative, that combine experimental knowledge with theoretical insight.

Conclusion

In summing up, it is vital to mention that this review emphasizes that major discoveries will be made at the LHC which will point towards new phenomena that physicists will want to explore using an appropriate new collider. This may call for more ingenuity and funding in order to achieve more of physics beyond the SM.

Furthermore, experiments at the LHC may indicate new physics at energy scales significantly beyond those that it can decisively reach. As a result, extension of the energy frontier beyond the reach afforded by the LHC will require the development of new technologies.

A muon collider or a very large hadron collider has the potential for supporting even higher energies and luminosities in the post-LHC era. Muon collider technology remains to be demonstrated, so the need is to focus on the development and validation of concepts. Present-day hadron collider technology could likely be used to construct a facility with a reach significantly beyond LHC, but the cost would be prohibitive. Hence efforts in this realm should focus on a reduction of cost through the use of advanced technologies.

Finally, development of both muon and hadron collider technologies must be pursued in a timely fashion to determine whether they represent technologically and economically viable options for reaching energies beyond those explored with LHC.

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