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The Standard Model of Particle Physics and What Lies Beyond: A View from the Bridge

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Abstract: The standard models of particle physics and of cosmology have been enormously successful in correlating a large amount of data. However, there are missing pieces and we are still far from what the ultimate model may look like. We give a broad perspective of both the achievements and of the missing pieces and discuss what may lie beyond.

Keywords: standard model; ΛCDM; beyond standard model physics

1. Introduction

This article is a contribution to Guido Barbiellini Amidei's memorial volume marking his several decades of contributions that include some of the critical experiments in particle physics in that period. They include the AdA project at Frascati, the world's first electron–positron collider, which opened a new era in accelerator physics, and experiments on electron–positron annihilation into hadrons, laying the groundwork for future collider-based research. His further contributions include those at ALEPH at the LEP collider which lead to precision measurements of the Z boson decay modes and of the electroweak parameters, which helped test the standard model (SM) of particle physics. After LEP Amidei contributed to the CMS experiment at the LHC including detector development and commissioning. In this article we trace the brief history of theoretical advances that lead to the eventual formulations of the standard model of particle physics. We also discuss what lies beyond the standard model including the emerging intertwining of particle physics and cosmology and the recent progress in this area.

2. Development of the Standard Model of Particle Physics

The formulation of the standard model of electroweak interactions was preceded by much work in the study of weak interactions specifically related to fermions that goes back to Enrico Fermi's theory of beta decay [1] using a contact interaction involving four fermions with only vector interaction among them. However, it was subsequently realized that a more general structure was needed to understand weak interactions and several different types of interactions were possible, i.e., involving bilinears including scalar, pseudoscalar, vector (V), axial vector (A), and tensor interactions. The appropriate linear combinations were then to be determined experimentally. The landscape of particle physics changed in 1956 after the work of T. D. Lee and C. N. Yang [2] that parity may not be conserved in weak interactions. This hypothesis was checked in 1957 by the work of C. S. Wu et al. [3] in the study of the angular distribution of electrons in beta decay of polarized ^{60}Co nuclei. The next major step was taken in 1957 by E. C. G. Sudarshan and R. E. Marshak [4] and independently by R. P. Feynman and M. Gell-Mann [5], that the weak interaction structure was $V-A$. The $V-A$ theory was tested in numerous experiments thereafter and was fully established by 1960. A historical review of the development of

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$V - A$ and its tests is given in Weinberg's 2009 paper [6]. As noted by Weinberg, the $V - A$ theory was the key to future developments. Thus, further work by a number of authors, including T. D. Lee and Julian Schwinger, proposed that the weak interactions involved both vector and axial vector fields where the spin 1 fields were massive. These ideas combined with the spontaneous symmetry breaking via the Higgs mechanism eventually resulted in the $SU(2)_L \times U(1)_Y$ theory of electroweak interactions [7–10], which was then shown to be a renormalizable theory [11]. The electroweak model was tested through the observation of weak neutral currents at CERN in the Gargamelle experiment [12], and by the discovery of the $W^{\pm}$ and Z^0 bosons at CERN in 1983 by the UA1 and UA2 Collaborations [13,14]. The final missing piece of the electroweak theory was the Higgs boson which was discovered in 2012 by ATLAS [15] and CMS [16]. In addition to the electro-weak theory, the standard model of particle physics contains $SU(3)_C$ gauge group which mediates color interactions between quarks, and leads to quantum chromo-dynamics (QCD) [17,18]. Scaling violations predicted by QCD are in conformity with deep inelastic scattering observed at SLAC and CERN, and three-jet events observed in e^+e^- annihilation at DESY confirmed gluon bremsstrahlung [19], providing direct evidence for the existence of gluons. Further, asymptotic freedom which is an intrinsic feature of QCD provides an understanding of deep inelastic scattering observed at SLAC [20]. Thus, the standard model of particle physics is currently tested to an unprecedented precision.

3. What May Lie Beyond SM

Standard model though highly successful has its limitations. These are both theoretical in nature, and also observational. On the observational side we now have strong evidence for dark matter and dark energy for which the standard model provides no clue. On the theoretical side, the main issue concerns the large hierarchy problem, namely the loop correction to the Higgs boson mass is quadratically divergent and one needs an extreme fine tuning to remove it. One of the prime candidates of physics beyond the standard model is supersymmetry [21,22], or more appropriately its localized form supergravity. Before proceeding further we note that, contemporaneous to the development of supersymmetry and supergravity theories, work on further unification beyond the SM was also in progress. Thus, in 1973 a unification of quarks and leptons was proposed [23] which was followed by the $SU(5)$ model of electroweak and strong interactions [24] and an $SO(10)$ model unifying in addition one generation of quarks and leptons in one irreducible representation of $SO(10)$ [25,26]. These models were extended to include supersymmetry and eventually to supergravity grand unification. Specifically, SUSY/supergravity grand unified theory has several advantages over the standard model and over non-supersymmetric grand unification. On the theory front, the SUSY/supergravity theory is free of quadratic divergences in the Higgs boson mass which is a major step forward. Further, while the gauge couplings of $U(1) \times SU(2)_L \times SU(3)_C$ do not unify in the non-supersymmetric unification, they do unify in supersymmetric unification (for a review see [27]). A similar situation holds for the case of Yukawa couplings for the third generation of quark–lepton matter. A more recent example is the Higgs boson mass. Within the standard model it could in principle be as large as the Fermi scale. However, in supersymmetric models it lies much lower. Specifically, it was shown [28], ahead of the discovery of the Higgs boson, that its mass should lie below 131 GeV within supergravity unified models [29]. This upper limit is respected by nature, in that experimentally the Higgs boson mass is currently set at 125.1 GeV. One of the interesting new phenomena in supergravity unified models is the prediction of sparticles [22] some of which may be observable at the high luminosity LHC. Thus, in $\tilde{g}$SUGRA [30] renormalization group evolution one finds that sparticle spectrum splits into a heavy part with masses in several TeV region, while others lie in the few hundred GeV region which would be accessible at high-luminosity LHC (HL-LHC). Thus, here one finds that, while the gluino, the heavy Higgs, and the squarks (except for the lighter stop) will be too heavy to be observed, the light chargino, the neutralino and the sleptons, specifically the stau, should be accessible at the high-luminosity LHC [31].

One of the important tests of grand unification is proton decay and its detection will provide a strong evidence of physics beyond the standard model and more specifically of unification of fundamental particles and of interactions [32]. Stringent limits on proton decay come from the Super-Kamiokande experiment where the most recent lifetime limit for the mode $p \to e^+\pi^0$ is $\tau/B > 2.4 \times 10^{34}$ years (90% CL) [33] and for the mode $p \to \bar{\nu}K^+$, the limit is $\tau/B > 5.9 \times 10^{33}$ years [34]. These experimental limits already exclude many grand unified models. A new generation of experiments aim to improve sensitivity by an order of magnitude. Thus, the Hyper-Kamiokande experiment scheduled to begin its operation in 2027 is expected to reach sensitivities of $\tau/B > 1 \times 10^{35}$ years for $p \to e^+\pi^0$ after 10 years [35]. Further, the Deep Underground Neutrino Experiment (DUNE) also aims to improve the sensitivity of the kaon decay mode due to its improved tracking and particle identification [36]. Finally, the Jiangmen Underground Neutrino Observatory (JUNO) may also look for proton decay modes involving invisible final states [37]. Together these experiments will probe a large part of the unified models of particle physics.

An alternative to SUSY is the composite Higgs boson model as a possible solution to the hierarchy problem. In these models the Higgs boson arises as a bound state of a strongly interacting sector [38]. Thus, strong interaction models with a global symmetry G broken spontaneously to a subgroup H gives rise to pseudo-Nambu–Goldstone bosons (PNSB). With appropriate choice of G and H one can generate the desired Higgs doublets for electroweak symmetry breaking. For example $G/H = SO(5)/SO(4)$ after spontaneous breaking gives rise to $SU(2)_L \times SU(2)_R$ PNSBs. A significant amount of phenomenology exists based on composite Higgs models. One of the main challenges here, however, relates to achieving UV completeness in this class of models. Further, supergravity and strings have also opened the way to the study of extra dimensional models [39–41] which represents another frontier for further study.

The emergence of supergravity and string models, in addition, have brought focus on hidden sectors or dark sectors that have begun to play an increasingly important role in particle physics phenomenology. Thus, the minimal dark portals include the dark Higgs [42] and the dark photon [43] as well as portals involving higher dimensional operators. These new sectors raise the possibility that dark matter may reside in part or even entirely in the dark sector. The same may be true of dark energy. A similar situation exists for axions, some of which may exist in the visible sector while others in the dark sector. There are various axionic searches underway including helioscopes which search for axions produced by the sun and haloscopes which search for axions in the dark matter halo of our galaxy (for a review of axions and ALPs see, e.g., [44]). An interesting possibility exists that axions may be ultralight, i.e., as light as 10^{-21}eV or even lighter which has important implications for phenomenology and specifically for dark matter [45–47]. We note that in the near future new data from LHC will be forthcoming allowing further tests of a broad set of models of physics beyond the standard model. Here the standard model effective field theory (SMEFT) which includes higher dimensional operators could be helpful in discriminating among the new physics models [48]. Further, over the coming years we expect more data from direct detection experiments which include LUX-ZEPLIN, XENONnT and PandaX-4T. Thus, LUX-ZEPLIN [49] has already put strong limits on WIMP–nucleon spin independent cross section so that $\sigma^{SI}_{\chi N} < 2.2 \times 10^{-48}$ cm^2 ($m_\chi = 43$ GeV/c^2). In the future we expect more stringent upper limits constraining new physics models even more stringently and eliminating some altogether.

Further, in recent years, the fields of particle physics and of cosmology have become increasingly intertwined [50–52]. This is due to their strong overlap specifically in two areas: dark matter and dark energy. Each of these areas are critical in models of particle physics and cosmology. Thus, dark matter models abound in particle physics from the lightest candidate involving an axion of mass around 10^{-21} eV to masses in the range of several TeV and beyond. However, there exists a strong constraint on dark matter from cosmology which arises from Big Bang nucleosynthesis which imposes severe constraint on the allowed degrees of freedom beyond the standard model. One of the major discoveries over the past several decades is that of dark energy by the Supernova Cosmology Project [53] and the High-Z Supernova Search Team [54] from the measurement of the brightness and redshifts of distant Type Ia supernovae that the universe is accelerating rather than decelerating. This observation implies the existence of negative pressure generated by what we call dark energy. The existence of dark energy was further confirmed by CMB data by WMAP [55] and by Planck [56]. The simplest way to simulate dark energy is to use the Λ term in Einstein's equations which, with inclusion of dark matter, leads to the standard ΛCDM model of cosmology. This model gives the equation of state (EoS) for dark energy so that $w = -1$ where $w = p/\rho$ with p being the pressure and ρ the energy density. The ΛCDM has been enormously successful in explaining a large amount of cosmological data. However, recently some tensions have arisen in the standard ΛCDM model due to different measurements of the Hubble parameter H_0 and of mass power spectrum parameter S_8. Thus, the Planck plus analysis [56] gives $H_0^{\rm Pl} = (67.4 \pm 0.5)$ km/s/Mpc while the analysis of the SHOES collaboration [57] gives $H_0^{\rm R22} = (73.04 \pm 1.04)$ km/s/Mpc. A similar situation holds for S_8. Here, the Planck experiment gives $S_8^{\rm Pl} = 0.834 \pm 0.016$, KiDS-1000 [58] gives $S_8^{\rm KiDS} = 0.759^{+0.024}_{-0.021}$. Since the Planck analysis is performed with ΛCDM, the significant deviations from other experiments lead to tensions for H_0 and S_8. A resolution of these tensions indicates the need for new physics beyond ΛCDM. Several extensions of the ΛCDM model have appeared in the literature, including the proposal for a dynamical origin for dark energy such as quintessence and the possibility of interactions between dark energy and dark matter such as interacting quintessence (see, $QCDM$ [59], and the references therein).

In addition to the H_0 and S_8 tensions noted above there are also other tensions within ΛCDM. An important new tension is related to EoS which, as noted earlier, gives $w = -1$ within ΛCDM, while the dark energy experiment DESI RD2 [60,61] shows a possible deviation from ΛCDM by 4.2σ. The analysis of DESI RD2, however, is based on use of the Chevallier–Polarski–Linder (CPL) parameterization [62,63] of the EoS based on $w(a) = w_0 + (1-a)w_a$, where a is the scale factor. However, CPL parametrization of EoS used in DESI RD2 analysis is too simple to fully capture the evolution of dark energy at late times and more non-trivial parametrizations are needed as discussed in several works such as [64].

Aside from the broad perspective given above, there are also other specific phenomena that have played and will play a role in the exploration of physics beyond the standard model. One such area is neutrino physics. The standard model predicts massless neutrinos while experiments via neutrino oscillations indicate masses for them. One of the sources for their masses is the well known see-saw mechanism which indicates the presence of a high scale for their generation. Further, CP violation in the neutrino sector has been observed and it is of interest to determine if it may have links to the CP violation that enters leptogenesis. There are two great unknowns regarding neutrino masses that need further exploration in the future. First, neutrino oscillation experiments only allow the determination of Δm^2. The absolute masses may also be determined from beta decay which looks for shape of the beta spectrum near its end point in the process $^3\mathrm{H} \to\ ^3\mathrm{He}^+ + e^- + \bar{\nu}_e$. Also, CMB analyses [56] and cosmic neutrinos [65] allow one to constraint absolute neutrino masses. Another important area of exploration is the neutrino mass hierarchy, i.e., whether it is normal or inverted which has significant implications for particle physics model building.

Another area for the exploration of fundamental physics has opened up recently after the observation of gravitational waves in black hole mergers in 2016 [66]. That observation has lead to an exploration of fundamental physics in a broader context using stochastic background of gravitational waves. There are various possible sources of stochastic gravitational waves, such as from first order phase transitions. These arise at finite temperatures [67,68] and give rise to stochastic gravitational waves [69]. Specifically supercooled phase transitions can generate gravitational waves in the nano-Hertz frequency region (see, e.g., [70] and the references therein) evidence for which has recently emerged from NANOGrav, EPTA, PPTA. Several other sources of stochastic gravitational waves exist such as from the decay of the inflaton into standard model particles [71–73]. It is also suggested that phase transitions may be linked to the generation of matter–antimatter asymmetry, and specially to baryogenesis. Other sources of gravitational waves are cosmic strings which can produce gravitational waves via loop oscillations, as well as via primordial black hole formation. In addition to the nano-Hertz frequency experiments there are currently other ongoing and proposed gravitational wave experiments which include LISA/VIRGO, Decigo and several others.These experiments will probe gravitational waves at different frequency regions and with different sensitivity and will allow us to probe the early universe close to the initial Big Bang time beyond the reach of particle physics experiments aside from the one on proton decay.

4. Conclusions

The standard model of particle physics is one of the most tested models in the history of particle physics. However, there are missing pieces in the standard model at the theoretical level. Further, experimentally, the model cannot account for dark matter and dark energy which are now firmly established to exist. There are, thus, strong reasons for the existence of new physics beyond the standard model which is expected to show up in the energy range of several TeV. Supersymmetry and supergravity are currently the leading candidates for such new physics whose predictions can be tested at HL-LHC. Further, over the past several decades, there has been an increasing intertwining of particle physics and cosmology. Also, much like the standard model of particle physics, cosmology also has its standard model, i.e., the ΛCDM model, which is Einstein gravity including a cosmological constant Λ coupled with dark matter. The ΛCDM model is highly successful in correlating a large amount of cosmological data. However, like the standard model of particle physics it is also under stress because of tensions between different measurements of the Hubble parameter and of the mass power spectrum S_8 at early times vs. late times. Additionally, recent experiments on dark energy indicate that it may be time dependent and not a constant as predicted by ΛCDM. This observation has given rise to a great amount of activity recently, which is still ongoing. Thus, most dynamical models of dark energy are particle physics models which illustrates the intrinsic intertwining of the fields of particle physics and cosmology.

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