

Chapter 2

Introduction to the Standard Model and Beyond

The Q_{weak} experiment is a precision test of the Standard Model. In this chapter we give an introduction to the SM, concentrating particularly on electroweak theory. Problems with the SM are reviewed, which leads naturally into a discussion on possible BSM physics and their experimental searches.

2.1 The Standard Model

Based on the $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge group, the SM successfully predicts the behaviour of three out of the four observed forces. The only one not included in this description is gravity. The strong interactions are a result of $SU(3)$ colour (hence ‘ c ’) symmetry, whereas the unified electromagnetic and weak interactions are accounted for by the $SU(2)_L \times U(1)_Y$ factor. The subscript L refers to the fact that the $SU(2)$ part acts only on left-handed fermions, while the Y factor is the *weak hypercharge*.

Interactions between the leptons and quarks which make up nuclear matter occur via the exchange of vector bosons. In the case of QCD, massless gluons are responsible for the strong force experienced by quarks, while the weak force is mediated by the massive $W^\pm$ and Z^0 bosons. The photon completes the force-carrier sector and mediates the familiar electromagnetic interactions.

Both leptons and quarks may be divided into three generations according to their mass and electric charge (cf. Table 2.1). Quarks, under the influence of the strong force, combine to form mesons (quark-antiquark pairs) and baryons (three quark systems). These *hadrons* in turn, form multiplets, whose structure is largely—since $SU(3)$ flavour is not exact—governed by the irreducible representations of $SU(3)$. The leptons on the other hand, experience only the weak and electromagnetic interactions. Completing the particle content of the SM is the recently discovered [1, 2] Higgs boson associated with the Higgs field, responsible for generating mass in the SM.

Table 2.1 Properties of the three generations of SM matter particles

Gen.	Quark	Charge	Mass (MeV)	Lepton	Charge	Mass (MeV)
I	u	$2/3$	$1.8\text{--}3.0$	e	-1	0.511
	d	$-1/3$	$4.5\text{--}5.3$	ν_e	0	$<2 \times 10^{-6}$
II	s	$-1/3$	$90\text{--}100$	μ	-1	106
	c	$2/3$	1.28×10^3	ν_μ	0	<0.19
III	t	$2/3$	1.73×10^5	τ	-1	1.78×10^3
	b	$-1/3$	4.18×10^3	ν_τ	0	<18.2

The data is taken from the Particle Data Group [3]

From these fundamental building blocks the rest of nuclear matter in the universe is presently understood to be constructed.

2.2 Electroweak Theory

The theoretical footings for the unification of the SM electroweak theory were first introduced by Glashow [4] in 1961. The massless vector bosons associated with this $SU(2) \times U(1)$ gauge symmetry are W_μ^i (where $i = 1, 2, 3$) and B_μ , whilst the couplings are g and g' . These gauge bosons are included in the SM in the kinetic terms of the Lagrangian,

$$\mathcal{L} = -\frac{1}{4} W_{\mu\nu}^i W^{\mu\nu i} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}, \quad (2.1)$$

where the field strength tensors are,

$$\begin{aligned} W_{\mu\nu}^i &= \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g\epsilon_{ijk} W_\mu^j W_\nu^k, \quad i, j, k = 1, 2, 3; \\ B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu. \end{aligned} \quad (2.2)$$

Under $SU(2)$ ‘weak isospin’ the left-handed fermions transform as doublets. The $U(1)$ gauge group acts on both left- and right-handed components of the fermion fields and is associated with a phase symmetry [5]. In order to generate the masses of the physical particles, the $SU(2) \times U(1)$ symmetry is spontaneously broken [6, 7] when minimising a potential,

$$V(\phi) = \mu^2 \phi^\dagger \phi + \frac{\lambda^2}{2} (\phi^\dagger \phi)^2,$$

involving a complex scalar doublet,

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}. \quad (2.3)$$

This is known as the Higgs mechanism [8–11].

After spontaneous symmetry breaking, the $U(1)_Q$ group is the only remaining unbroken symmetry. Additionally, the weak mediators end up acquiring mass leaving the photon as the sole massless vector boson. Quantum electrodynamics (QED) is based on this $U(1)_Q$ group. Proof of the renormalisability of such spontaneously broken gauge theories by t’Hooft and Veltman [12–14] in the early 1970s completed the theoretical development of electroweak theory. Experimentally, however, there still remained some puzzling issues.

Parity Violation in EW Theory

In 1956 Lee and Yang [15] put forward the idea of parity non-conservation in weak interactions. An exceptionally radical thought at the time, this was soon verified experimentally by Wu et al. [16] and confirmed by a group lead by Lederman [17]. Both of these experiments involved charged current reactions; however, Glashow’s theory also predicted a small amount of parity violation through the neutral current (NC) interaction term

$$J_{int}^\mu = \frac{g}{2 \cos \theta_W} J_{NC}^\mu(x) Z_\mu(x), \quad (2.4)$$

where,

$$J_{NC}^\mu(x) = \sum_i \bar{\psi}_i(x) \gamma^\mu (g_V^i - g_A^i \gamma^5) \psi_i(x), \quad (2.5)$$

and $Z_\mu(x)$ is the Z^0 -boson field. The fermion (anti-fermion) fields are given by ψ_i ($\bar{\psi}_i$), and the vector and axial-vector couplings,

$$g_V^i \equiv t_{3L}^i - 2q_i \sin^2 \theta_W, \quad (2.6)$$

$$g_A^i \equiv t_{3L}^i, \quad (2.7)$$

where t_{3L}^i is the weak isospin of the fermion i and q_i the charge.

After several conflicting experimental results [18–20], PV in neutral currents was finally confirmed by Prescott et al. [21] in 1978 using electron–deuterium scattering and reaffirmed by a second experiment the following year [22]. The measured asymmetries are shown in Fig. 2.1. Together with the indirect [23–25] and direct [26, 27] observations of the Z^0 -boson at CERN, these results firmly established the $SU(2) \times U(1)$ theory as the principal description of the unified weak and electromagnetic interactions.

Since then the theory has proven to be extremely robust, successfully predicting the values of physical observables to unprecedented levels of precision. Advancements in technologies has meant that it is now possible to search for deviation between

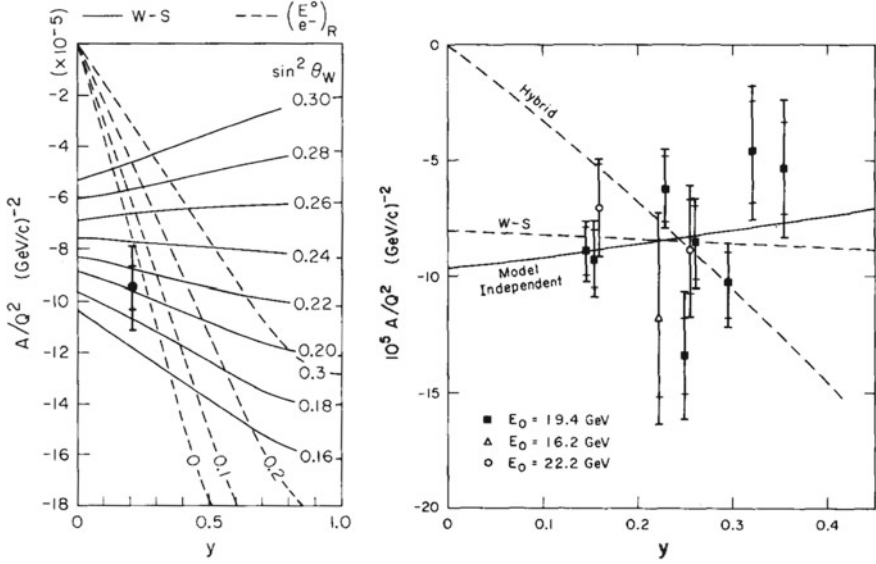


Fig. 2.1 Parity violation in e - d scattering as observed by Prescott et al. [21, 22]. On the left-hand plot, the dashed line represents the same ‘Hybrid’ model shown in the right-hand figure. Both asymmetries (A) are normalised by the momentum transfer (Q^2) and plotted against the fraction of energy lost by the incoming electron (y)

experiments and theory at the parts per billion (ppb) level. In Sects. 3.1 and 3.2 we will discuss these developments in more detail.

The Weak Mixing Angle

Mixing of the four vector fields, W_μ^i and B_μ , gives,

$$\begin{aligned} W_\mu^\pm &= \frac{1}{\sqrt{2}} (W_\mu^1 \mp W_\mu^2), \\ Z_\mu &= \frac{1}{\sqrt{g^2 + g'^2}} (gW_\mu^3 - g'B_\mu), \\ A_\mu &= \frac{1}{\sqrt{g^2 + g'^2}} (g'W_\mu^3 + gB_\mu), \end{aligned} \quad (2.8)$$

where the $W_\mu^\pm$ and Z_μ are the mediator fields of the weak interactions and A_μ is the photon field of the electromagnetic force.

Alternatively, one can define the weak mixing angle (also referred to as the *Weinberg angle*) in terms of the coupling constants,

$$\sin \theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}, \quad \cos \theta_W = \frac{g}{\sqrt{g^2 + g'^2}}, \quad (2.9)$$

such that,

$$\begin{aligned} Z_\mu &= \cos \theta_W W_\mu^3 - \sin \theta_W B_\mu, \\ A_\mu &= \sin \theta_W W_\mu^3 + \cos \theta_W B_\mu. \end{aligned} \quad (2.10)$$

In order to verify experimentally, a renormalised definition of $\sin^2 \theta_W$ is required. At lowest order in perturbation theory,

$$\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}, \quad (2.11)$$

and this expression was used extensively earlier on. However, it also induced misleading radiative corrections involving the top quark mass which meant that an alternative definition was needed [28].

Today, the most commonly used definition of the weak mixing angle comes from the modified minimal subtraction ($\overline{\text{MS}}$) renormalisation scheme where,

$$\sin^2 \theta_W(\mu)_{\overline{\text{MS}}} = e^2(\mu)_{\overline{\text{MS}}} / g^2(\mu)_{\overline{\text{MS}}}, \quad (2.12)$$

with μ representing the sliding energy scale. Theoretically motivated, this definition is, however, unphysical and requires global fits to data in order to obtain an experimental value [5].

The running of $\sin^2 \theta_W$ with respect to the energy, allows for straightforward testing of the SM. By measuring the weak mixing angle at different energies, one directly examines the accuracy of the SM's predictions. In Fig. 2.2 we show a number of past, present and future low-energy experiments, whose aim is to check the running of $\sin^2 \theta_W$.¹ (Note that in this case $\sin^2 \theta_W$ is shown as a function of the momentum transfer Q as opposed to μ .)

2.3 Beyond the SM

Perhaps one of the most famous examples of agreement between the SM and experiment is the anomalous magnetic moment of the electron where,

$$\begin{aligned} a_e(\text{Exp}) &= 11596521807.6 \pm 2.7 \times 10^{-13}, \\ a_e(\text{SM}) &= 11596521817.8 \pm 7.7 \times 10^{-13}, \end{aligned}$$

and the $a_e(\text{SM})$ [35] is the theory prediction. We, however, are primarily interested in those observables which relate to PV in the SM. In Table 2.2 we show the current

¹The final value for $\sin^2 \theta_W$ extracted from the NuTeV experiment [29] is the subject of considerable debate [30–33]. Despite being shown to lie significantly above the SM prediction in Fig. 2.2, additional corrections such as sea-quark effects result in agreement with theory [28].

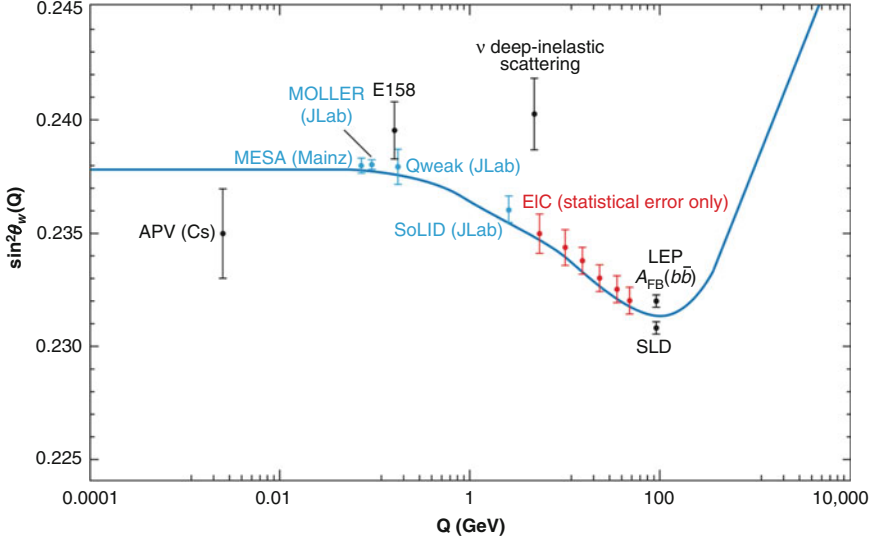


Fig. 2.2 The running of $\sin^2 \theta_W$ and the current experimental status [28]. *Black* data points represent published results, while the *blue* and *red* points are projections for future experiments. The uncertainty on the theory prediction is of order the thickness of the *curve*, where at low energies this corresponds to $\pm 7 \times 10^{-5}$ [3, 34]

Table 2.2 Standard Model parity-violating parameters compared with their experimental values [3]

Observable	Experimental value	SM prediction
$C_{1u} + C_{1d}$	0.1537 ± 0.0011	0.1530(1)
$C_{1u} - C_{1d}$	-0.516 ± 0.014	-0.5300(3)
$C_{2u} + C_{2d}$	-0.21 ± 0.57	-0.0089
$C_{2u} - C_{2d}$	-0.077 ± 0.044	-0.0627(5)
Q_W^e	-0.0403 ± 0.0053	-0.0474(5)

Q_W^e is the weak charge of the electron

state-of-the-art for a number of these measurements, where C_{1i} and C_{2i} are defined in terms of the effective four-point interactions,

$$\mathcal{L}_{\text{NC}}^{eq} = -\frac{G_F}{\sqrt{2}} \sum_{i=u,d} \left[C_{1i} \bar{e} \gamma_\mu \gamma^5 e \bar{q}_i \gamma^\mu q_i + C_{2i} \bar{e} \gamma_\mu e \bar{q}_i \gamma^\mu \gamma^5 q_i \right], \quad (2.13)$$

with G_F the Fermi coupling constant. At tree level,

$$C_{1i} = 2g_A^e g_V^i, \quad C_{2i} = 2g_V^e g_A^i, \quad (2.14)$$

where $g_A^e = -1/2$ and $g_V^e = -(1 - 4 \sin^2 \theta_W)/2$. The quark couplings,

$$g_V^u = \frac{1}{2} - \frac{4}{3} \sin^2 \theta_W, \quad g_A^u = \frac{1}{2},$$

$$g_V^d = -\frac{1}{2} + \frac{2}{3} \sin^2 \theta_W, \quad g_A^d = -\frac{1}{2},$$

are the same as those in Eq. (2.7).

In spite of the SM's many achievements it is seen as incomplete. A number of subatomic and astrophysical observables have lead to the notion that there is a deeper, more fundamental theory, of which the SM is but a low-energy effective theory. Neutrino masses, the rotational speed of galaxies, and the inexplicably low mass of the Higgs boson are all problematic in the SM, and give strength to this understanding. In the following section we expand on some of these difficulties.

Motivating New Physics

Although the list below is by no means complete, it contains many of the most important motivating factors of searches for NP. For a more comprehensive set, see for example, Refs. [5, 36, 37].

Gravity

Unlike the strong, weak and electromagnetic forces that can all be described at the quantum level, gravity is currently only successfully realised classically. Attempts to quantise general relativity run into the problem that the resulting theory is non-renormalisable. Furthermore, while it may be possible to combine general relativity to the SM by hand, gravity does not unify with the other three interactions at a fundamental level. It is expected that a more complete theory would include the correct quantum description of gravity as well as unifying it with the SM forces.

Hierarchy Problem

The mass-generating Higgs mechanism results in a neutral scalar boson of spin 0. Experimental results from the LHC give the mass of the Higgs boson to be ~ 125 GeV [1, 2]. Theoretically, however, such a light mass can only be obtained by an artificially large amount of fine tuning.

We may write the Higgs mass as,

$$m_H^2 = m_{H,bare}^2 + \mathcal{O}(\lambda, g^2, h^2)\Lambda^2, \quad (2.15)$$

where λ is Higgs self-coupling and g and h are the couplings to the gauge bosons and fermions. The bare Higgs mass receives corrections from higher order loop diagrams some of which are shown in Fig. 2.3. These diagrams are proportional to Λ —the scale at which the ultraviolet divergences are cut off—and are quadratically divergent. Should there be no physics between the electroweak scale ($\Lambda \sim 10^3$ GeV) and the Planck scale ($\Lambda \sim 10^{19}$ GeV), the cancellation required to get a Higgs mass of 125 GeV must occur to 30 decimal places [5]. Such fine tuning is seen as highly unnatural and any BSM physics which might provide a solution to this problem is considered to be worth examining.

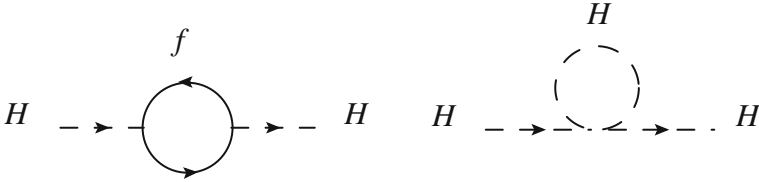


Fig. 2.3 Examples of one loop corrections to the physical Higgs mass

Neutrino Masses

At the time when the SM was originally formulated there was no empirical evidence for massive neutrinos. They were therefore incorporated in the SM as massless particles. Since then however, experimental data [38–40] indicates that neutrinos oscillate, i.e. they change flavour as they propagate. This means that in fact the neutrinos must have some mass, albeit very small. Although masses for neutrinos may be incorporated into the SM by either adding extra right-handed states, or by the ‘seesaw mechanism’ [41–43], there is still no experimental evidence to decide between the two scenarios. Since these additions are not a part of the original SM, NP is still needed to offer a more satisfactory solution.

Another question which the SM fails to answer is whether neutrinos are Dirac or Majorana particles.

Gauge Coupling Unification

In the SM, the effective gauge couplings—corresponding to the strength of the forces—may be written as functions of the energy scale. If the running of couplings are plotted together as shown in Fig. 2.4, it is clear that they do not meet at a single point. The failure of the coupling constants to unify is seen as a drawback of the SM and NP is required to obtain such unification.

Dark Matter

Gravitational lensing, star velocities in spiral galaxies and large-scale cosmological structure all suggest that the universe contains additional non-nuclear matter. Invisible electromagnetically, thus ‘dark’, it is thought to make up $\sim 22\%$ of the total energy content of the universe [5]. Although its presence is currently inferred only from gravitational interactions, it is also possible that dark matter (DM) interacts weakly.

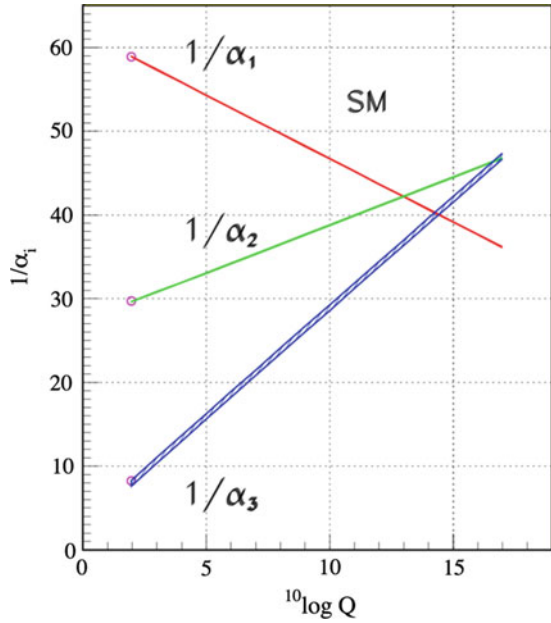
While there have been several SM based explanations for dark matter, such as neutrinos, or ‘MACHOs’, (Massive Compact Halo Objects) most of these candidates fail to explain the full range of current observations. In the case of neutrinos, their masses are too light to give the correct relic density and their velocities too high to allow for formation of the observed large scale structures. MACHOs on the other hand, lack a credible mechanism for creating the amount of objects needed to account for the masses of the galaxies.

Fig. 2.4 Non-unification of the gauge couplings in the SM [44]. The couplings are defined as

$$\alpha_1 \equiv 5/3 [g^2/(4\pi)],$$

$$\alpha_2 \equiv g^2/(4\pi) \text{ and}$$

$$\alpha_3 \equiv g_s^2/(4\pi)$$



The failure of the SM to offer a suitable solution for DM, has left physicists little option but to look outside the SM. A number of candidates e.g. axions, gravitinos, even non-Newtonian gravity have all at various points been considered as possible explanations. The leading candidate, however, remains weakly interacting massive particles (WIMPs) and to be given serious attention most BSM theories require such a particle.

Candidates for BSM Physics

Given the range of issues with the SM, it is perhaps not surprising that there is no shortage of contenders for alternative physics models. Although there is yet to be any experimental verification of any of these theories—either via direct or indirect detection—there remains a large body of work devoted to studying their implications. This next section looks at some of the more prominent BSM theories.

Supersymmetry

One of the best theoretically motivated extensions of the SM is supersymmetry (SUSY). Originally introduced by Wess and Zumino [45], SUSY works by extending the Poincaré algebra [46] to include spinor generators. This successfully negotiates the Coleman-Mandula No-go theorem [47], which states that the most general symmetry group of the S-Matrix is the cross product of the spacetime transformations and an internal symmetry (such as a gauge theory).

The spinor generators Q_α act on fermions (bosons) transforming them to bosons (fermions),

$$\begin{aligned} Q_\alpha |f\rangle &= |b\rangle, \\ Q_\alpha |b\rangle &= |f\rangle. \end{aligned}$$

This means that each particle acquires an additional superpartner—the fermions a bosonic partner, and the bosons a fermionic partner. The Higgs sector is, moreover, extended to two doublets.

One of the most attractive properties of SUSY is that it provides a natural DM particle. WIMPs are considered prime candidates for dark matter because they are both heavy enough ($\sim 10^2\text{--}10^3$ GeV [5]), to allow for the observed rotation speeds of the stars and only weakly interacting, accounting for inability to detect it through the electromagnetic spectrum. With the addition of so-called R-parity—necessary for proton stability—the lightest supersymmetric particle (LSP) becomes stable making it an ideal DM possibility.

SUSY theories may also help solve the hierarchy problem. The Higgs self-energy loops containing additional supersymmetric particles cancel out those that appear in the SM (cf. Fig. 2.3), removing the need for artificial fine tuning. In combination with grand unified theories, SUSY also allows for the unification of the coupling constants. Another attractive quality of SUSY is that it opens up the possibility of a quantum description of gravity.

Because SUSY provides solutions to many of the SM's problems, it is one of the most extensively studied BSM theories. Experimentally, there are a considerable number of searches under way at the LHC. In detectors such as ATLAS and CMS, the LSP may be inferred from missing energy signatures. Other astrophysical experiments hope to see signs of SUSY particles indirectly by measuring self-annihilation products such as gamma rays.

Extra Dimensions

The LHC currently looks for signs of extra spatial dimensions also. The simplest extension to the standard four-dimensional spacetime involves a fifth, circular spatial dimension [48, 49]. Given that this additional dimension has not yet been observed, its radius should be small. This extra dimension then results in a tower of massive states called a *Kaluza-Klein tower*. These momentum states may be searched for in modern detectors.

Theoretical motivation for extra dimensions comes from both string theory and the ability to incorporate gravity with the three other forces. As of today, there is yet to be any experimental evidence for extra dimensions.

Technicolour

Finally, we mention technicolour. In these types of theories electroweak symmetry is broken by an additional non-abelian gauge interaction removing the need for a scalar (Higgs) field and the associated hierarchy problem. This is attractive since it removes the fine tuning that might otherwise appear.

Experimental Searches

The LHC is just one of a multitude of experiments currently under way, whose goal is to discover new physics. These searches are often divided into three ‘frontiers’—the Energy, Intensity, and Cosmic frontiers. Although they incorporate more than just BSM experiments these divisions are still useful classification tools. In this section we give a broad overview of these NP searches, for a more complete review see Refs. [5, 28].

Energy Frontier

This category is dominated by the Large Hadron Collider. With four detectors (ATLAS, CMS, ALICE and LHCb) and an anticipated final centre-of-mass energy of 14 TeV, the LHC is the largest and most powerful particle accelerator yet created. Its range of NP searches includes all those previously discussed i.e. supersymmetry [50], extra dimensions [51] and technicolour [52], as well as others like microscopic black holes [53]. Although they have yet to observe any of these phenomena, these experiments have placed new constraints on the energy scales of BSM physics. With the upgrade of the LHC almost complete, a new range of experiments will begin which will continue to increase these limits. Other planned experiments at the energy frontier include the International Linear Collider and the Future Circular Collider.

Unfortunately, the nature of the LHC experiments means that it would be difficult to discover the precise properties of any NP observed. To do this requires experiments at the intensity frontier.

Intensity Frontier

This technique provides an alternative approach to the ‘brute-force’ method discussed above. In these types of experiments, beams of high intensity are focused on a target resulting in measurements which are repeated many times over. By building up the statistics and ensuring that the systematic errors are under control, these experiments make precision measurements of SM observables with hope of detecting ‘smoking-gun’ signals of new physics.

The previously mentioned Q_{weak} experiment [54], MOLLER [55] and the E08-011 experiment [56], all fall under this category. Further examples include the proposed 11 GeV PVDIS [57] experiment, the measurement of the proton radius [58] and those involving the neutrino mixing parameters [59].

Another important field of research which falls within this grouping is the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [60, 61]. One of the main aims of flavour physics is to precisely determine the CKM matrix elements. Experiments such as those at Belle [62], BaBar [63] and LHCb [64] all play significant roles in this area.

Cosmic Frontier

In this category, observations are done on the cosmos. Optical, radio and even ‘neutrino’ telescopes such as ICECUBE are used to provide a better picture of the Universe. Techniques such as gravitational lensing have delivered key evidence [65] for

dark matter and further observations may well answer remaining questions on the nature of DM. Additionally, studies of cosmic rays [66, 67] provide windows into particle collisions at energies many orders of magnitude greater than those currently available at modern accelerators.

References

1. ATLAS Collaboration, G. Aad et al., Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Phys. Lett. B* **716**, 1–29 (2012)
2. CMS Collaboration, S. Chatrchyan et al., Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Phys. Lett. B* **716**, 30–61 (2012)
3. J. Beringer et al., Review of particle physics (RPP). *Phys. Rev. D* **86**, 010001 (2012)
4. S.L. Glashow, Partial symmetries of weak interactions. *Nucl. Phys.* **22**, 579–588 (1961)
5. P. Langacker, *The Standard Model and Beyond* (CRC Press, Boca Raton, 2010)
6. A. Salam, Weak and electromagnetic interactions. *Conf. Proc. C* **680519**, 367–377 (1968)
7. S. Weinberg, A model of leptons. *Phys. Rev. Lett.* **19**, 1264–1266 (1967)
8. G.S. Guralnik, C.R. Hagen, T.W.B. Kibble, Global conservation laws and massless particles. *Phys. Rev. Lett.* **13**, 585–587 (1964)
9. F. Englert, R. Brout, Broken symmetry and the mass of gauge vector mesons. *Phys. Rev. Lett.* **13**, 321–323 (1964)
10. P.W. Higgs, Broken symmetries and the masses of gauge bosons. *Phys. Rev. Lett.* **13**, 508–509 (1964)
11. P.W. Higgs, Broken symmetries, massless particles and gauge fields. *Phys. Lett.* **12**, 132–133 (1964)
12. G. 't Hooft, Renormalizable Lagrangians for massive Yang-Mills fields. *Nucl. Phys. B* **35**, 167–188 (1971)
13. G. 't Hooft, M.J.G. Veltman, Regularization and renormalization of gauge fields. *Nucl. Phys. B* **44**, 189–213 (1972)
14. G. 't Hooft, M.J.G. Veltman, Combinatorics of gauge fields. *Nucl. Phys. B* **50**, 318–353 (1972)
15. T.D. Lee, C.N. Yang, Question of parity conservation in weak interactions. *Phys. Rev.* **104**, 254–258 (1956)
16. C.S. Wu, E. Ambler, R.W. Hayward, D.D. Hoppes, R.P. Hudson, Experimental test of parity conservation in beta decay. *Phys. Rev.* **105**, 1413–1414 (1957)
17. R.L. Garwin, L.M. Lederman, M. Weinrich, Observations of the failure of conservation of parity and charge conjugation in meson decays: the magnetic moment of the free muon. *Phys. Rev.* **105**, 1415–1417 (1957)
18. P.E.G. Baird et al., Search for parity nonconserving optical rotation in atomic bismuth. *Phys. Rev. Lett.* **39**, 798–801 (1977)
19. L.M. Barkov, M.S. Zolotarev, Observation of nonconservation of parity in atomic transitions. *JETP Lett.* **27**, 357 (1978)
20. L.L. Lewis, J.H. Hollister, D.C. Soreide, E.G. Lindahl, E.N. Fortson, Upper limit on parity nonconserving optical rotation in atomic bismuth. *Phys. Rev. Lett.* **39**, 795–798 (1977)
21. C.Y. Prescott et al., Parity nonconservation in inelastic electron scattering. *Phys. Lett. B* **77**, 347–352 (1978)
22. C.Y. Prescott et al., Further measurements of parity nonconservation in inelastic electron scattering. *Phys. Lett. B* **84**, 524 (1979)
23. F.J. Hasert et al., Observation of neutrino like interactions without muon or electron in the Gargamelle neutrino experiment. *Phys. Lett. B* **46**, 138–140 (1973)
24. F.J. Hasert et al., Search for elastic ν_μ electron scattering. *Phys. Lett. B* **46**, 121–124 (1973)
25. F.J. Hasert et al., Observation of neutrino like interactions without muon or electron in the Gargamelle neutrino experiment. *Nucl. Phys. B* **73**, 1–22 (1974)

26. G. Arnison et al., Experimental observation of lepton pairs of invariant mass around 95-GeV/c² at the CERN SPS collider. *Phys. Lett. B* **126**, 398–410 (1983)
27. P. Bagnaia et al., Evidence for $Z^0 \rightarrow e^+ e^-$ at the CERN anti-p p collider. *Phys. Lett. B* **129**, 130–140 (1983)
28. K.S. Kumar, S. Mantry, W.J. Marciano, P.A. Souder, Low energy measurements of the weak mixing angle. *Annu. Rev. Nucl. Part. Sci.* **63**, 237–267 (2013)
29. G.P. Zeller et al., A Precise determination of electroweak parameters in neutrino nucleon scattering. *Phys. Rev. Lett.* **88**, 091802 (2002)
30. W. Bentz, I.C. Cloet, J.T. Londergan, A.W. Thomas, Reassessment of the NuTeV determination of the weak mixing angle. *Phys. Lett. B* **693**, 462–466 (2010)
31. S.J. Brodsky, I. Schmidt, J.J. Yang, Nuclear antishadowing in neutrino deep inelastic scattering. *Phys. Rev. D* **70**, 116003 (2004)
32. K.-P.O. Diener, S. Dittmaier, W. Hollik, Electroweak higher-order effects and theoretical uncertainties in deep-inelastic neutrino scattering. *Phys. Rev. D* **72**, 093002 (2005)
33. M. Hirai, S. Kumano, T.-H. Nagai, Nuclear modification difference between $u(v)$ and $d(v)$ distributions and its relation to NuTeV $\sin^2 \theta(W)$ anomaly. *Phys. Rev. D* **71**, 113007 (2005)
34. J. Erler, M.J. Ramsey-Musolf, The weak mixing angle at low energies. *Phys. Rev. D* **72**, 073003 (2005)
35. T. Aoyama, M. Hayakawa, T. Kinoshita, M. Nio, Complete tenth-order QED contribution to the muon $g-2$. *Phys. Rev. Lett.* **109**, 111808 (2012)
36. G. Jungman, M. Kamionkowski, K. Griest, Supersymmetric dark matter. *Phys. Rep.* **267**, 195–373 (1996)
37. F. Quevedo, S. Krippendorfer, O. Schlotterer, Cambridge Lectures on Supersymmetry and Extra Dimensions (2010)
38. K.S. Hirata et al., Observation of a small atmospheric muon-neutrino/electron-neutrino ratio in Kamiokande. *Phys. Lett. B* **280**, 146–152 (1992)
39. Q.R. Ahmad et al., Direct evidence for neutrino flavor transformation from neutral current interactions in the Sudbury Neutrino Observatory. *Phys. Rev. Lett.* **89**, 011301 (2002)
40. D. Raymond, D.S. Harmer, K.C. Hoffman, Search for neutrinos from the sun. *Phys. Rev. Lett.* **20**, 1205–1209 (1968)
41. T. Yanagida, Horizontal symmetry and masses of neutrinos. *Conf. Proc. C* **7902131**, 95–99 (1979)
42. M. Gell-Mann, P. Ramond, R. Slansky, Complex spinors and unified theories. *Conf. Proc. C* **790927**, 315–321 (1979)
43. P. Minkowski, $\mu \rightarrow e\gamma$ at a rate of one out of 1-billion muon decays. *Phys. Lett. B* **67**, 421 (1977)
44. W. de Boer, C. Sander, Global electroweak fits and gauge coupling unification. *Phys. Lett. B* **585**, 276–286 (2004)
45. J. Wess, B. Zumino, Supergauge transformations in four-dimensions. *Nucl. Phys. B* **70**, 39–50 (1974)
46. R. Haag, J.T. Lopuszanski, M. Sohnius, All possible generators of supersymmetries of the s matrix. *Nucl. Phys. B* **88**, 257 (1975)
47. S.R. Coleman, J. Mandula, All possible symmetries of the s matrix. *Phys. Rev.* **159**, 1251–1256 (1967)
48. T. Kaluza, On the problem of unity in physics. *Sitzungsber. Preuss. Akad. Wiss. Berl. (Math. Phys.)* 966–972 (1921)
49. O. Klein, Quantum theory and five-dimensional theory of relativity. *Z. Phys.* **37**, 895–906 (1926)
50. M. Stoye, SUSY searches at CMS. *Nuovo Cim. C* **035**, 333–340 (2012)
51. ATLAS and CMS Collaborations, D. Teyssier, LHC results and prospects: beyond standard model. CMS-CR-2014-022 (2014)
52. G. Azuelos, P. Depommier, R. Mazini, K. Strahl, Search for technicolor signals with the ATLAS detector. ATL-PHYS-99-020 (1999)

53. ATLAS Collaboration, G. Aad et al. Search for microscopic black holes and string balls in final states with leptons and jets with the ATLAS detector at $\sqrt{s} = 8$ TeV. JHEP **1408**, 103 (2014)
54. D.S. Armstrong et al., The Qweak experiment: a search for new physics at the TeV scale via a measurement of the proton's weak charge. JLAB-PHY-12-1478 (2012)
55. J. Mammei, The MOLLER experiment. Nuovo Cim. C **035N04**, 203–208 (2012)
56. D. Wang et al., Measurement of the parity-violating asymmetry in electron-deuteron scattering in the nucleon resonance region. Phys. Rev. Lett. **111**, 082501 (2013)
57. P.A. Souder, Parity-violating PVDIS with solid. AIP Conf. Proc. **1441**, 123–125 (2012)
58. R. Pohl et al., The size of the proton. Nature **466**, 213–216 (2010)
59. Daya Bay Collaboration, F.P. An et al., Independent measurement of θ_{13} via neutron capture on hydrogen at daya bay. Phys. Rev. D **90**, 071101 (2014)
60. M. Kobayashi, T. Maskawa, CP violation in the renormalizable theory of weak interaction. Prog. Theor. Phys. **49**, 652–657 (1973)
61. N. Cabibbo, Unitary symmetry and leptonic decays. Phys. Rev. Lett. **10**, 531–533 (1963)
62. K. Ikado et al., Evidence of the purely leptonic decay $B \rightarrow \tau^- \bar{\nu}(\tau)$. Phys. Rev. Lett. **97**, 251802 (2006)
63. B. Aubert et al., Observation of CP violation in the B^0 meson system. Phys. Rev. Lett. **87**, 091801 (2001)
64. R. Aaij et al., Measurement of the CKM angle γ from a combination of $B^\pm \rightarrow Dh^\pm$ analyses. Phys. Lett. B **726**, 151–163 (2013)
65. D. Clowe et al., A direct empirical proof of the existence of dark matter. Astrophys. J. **648**, L109–L113 (2006)
66. A. Aab et al., A targeted search for point sources of EeV neutrons. Astrophys. J. **789**, L34 (2014)
67. A. Aab et al., A search for point sources of EeV photons. Astrophys. J. **789**, 160 (2014)

Hadron Structure in Electroweak Precision
Measurements

Hall, N.L.

2016, XIV, 120 p. 47 illus., 29 illus. in color., Hardcover

ISBN: 978-3-319-20220-4