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Chapter 1

The Standard Model of Particle Physics

If you wish to make an apple pie from scratch, you must first invent the universe.

–Carl Sagan, *Cosmos: A Personal Voyage*

As it stands, what has become known as the 'Standard Model (SM) of Particle Physics' is nothing less than one of the greatest achievments of mankind, due to both the magnitude by which it has changed our perception of the underlying nature of the universe and to the clever methods and tinkerings by which this nature was unveiled by many clever physicists whose history has become veritable lore. In terms of imagination and insight, it is second only to the special and general theories of relativity – though the fields are nevertheless intricately intertwined.

Not considering the scientific progress made in the 18^{th} and 19^{th} centuries, and ignoring the ancient Greeks despite their fabled invention of atomic theory, the physical insights and major work that led to the current picture of elementary particle physics described by the SM began with the *annus mirabilis* papers of Albert Einstein in the year 1905 [1, 2, 3]. In these papers, Einstein was able to shed light on the quantization of electromagnetic radiation (building off of the seminal work of Max Planck [4]) and introduce the special theory of relativity. These works laid the conceptual and philosophical groundwork for the major breakthroughs in fundamental physics of 20^{th} century physics: from the 'old quantum theory' of Bohr and Sommerfeld in the early 1900's to the equivalent wavefunction and matrix-mechanics formulations of Schrödinger and Heisenberg that coalesced into 'modern' quantum mechanics in the mid-1920's. The modern approach, non-relativistic at its heart, provided a sufficient mathematical and interpretable framework in which to work and match predictions to observed phenomena, old and new. It has for the most part remained unchanged and is the quantum mechanics that is taught to students at both the undergraduate and graduate level to this very day. It is the theory that has since revolutionised all aspects of the physical sciences and technologies that dictate our everyday-lives. In the mid-1920's, however, despite large efforts put forth by the forbears of modern quantum mechanics, the quantum-mechanical world had yet to be made consistent with Einstein's theory of relativity — a requirement that must be met for all consistent physical theories of nature. It was the insight of Paul Dirac who was finally able to successfully marry the theory of the quantum with that of relativity when he introduced his relativistic quantum-mechanical treatment of the electron in 1927 and 1928 [5, 6].[1] This work provided the starting point for a decades-long search of a consistent quantum-mechanical and relativistic treatment of electrodynamics, known as *quantum electrodynamics* (QED). The search for QED ended at the end of the 1940's with the groundbreaking work of Dyson, Feynman, Schwinger, and Tomanaga [9, 10, 11, 12, 13, 14, 15, 16] that introduced the covariant and gauge invariant formulation of QED — the first such relativistic quantum field theory (QFT). QED allowed the physcists to make predictions that agreed with observation at unprecedented levels of accuracy and has since led to the adoption of its language and mathematical toolkit as the foundational framework in which to construct models that accurately describe nature.[2] The SM is no less than an ultimate conclusion of these works: a consistent set of relativistic quantum field theories, using the language developed by Feynman et al., that describes essentially all aspects of the known particles and forces that make up the observed universe.

1.1 Particles and Forces

There are four known forces at work in the universe today: electromagnetism, the weak interaction, the strong interaction, and gravity. All of these forces have been arrived at empirically, with physicists following experimental clues, and their basic behaviors deduced after long trials of effort. The SM encompasses all of these forces except for gravity, which currently is only best described by the classical (i.e. not quantum) theory of geometrodynamics, or Einstein's general relativity. Gravitational interactions are incredibly weak, however, and are not relevant to the types of particle interactions that we are currently (experimentally) sensitive to. Electromagnetism is by far the most familiar, as it is the force

[1] A complete history of the people and ideas involved in the development of the modern theory of Quantum Mechanics can be found in references [7, 8], and the references therein.

[2] For a complete discussion of the developments leading up to QED, see the fabulous book by S. Schweber [17].

most commonly experienced and is what is at work in our everyday life (reaction forces between tables and chairs, friction, wall-plugs, batteries, DNA structure, etc...) and what students are first presented in their physics studies. The weak force is responsible for things like radioactive decay which makes possible, for example, the process of nuclear β-decay and nuclear fission, the process that fuels our sun. The strong force is what binds protons and neutrons together, and thus is resonsible for holding together most of (ordinary) the matter in the universe.[3]

Table 1.1: The particle content of the SM and their transformation properties under the SM gauge groups, prior to electroweak symmetry breaking.

	Field Label	Content	Spin	$\mathcal{U}(1)$ $(=\mathcal{Y})$	$\mathcal{SU}(2)$	$\mathcal{SU}(3)$
Quarks	Q_i	$(u_\mathrm{L},\, d_\mathrm{L}),\, (c_\mathrm{L},\, s_\mathrm{L}),\, (t_\mathrm{L},\, b_\mathrm{L})$	1/2	1/6	**2**	**3**
	$u_{\mathrm{R},i}$	u_R	1/2	2/3	**1**	**3**
	$d_{\mathrm{R},i}$	d_R	1/2	−1/3	**1**	**3**
Leptons	L_i	$(e_\mathrm{L},\, \nu_{e,\mathrm{L}}),\, (\mu_\mathrm{L},\, \nu_{\mu,\mathrm{L}}),\, (\tau_\mathrm{L},\, \nu_{\tau,\mathrm{L}})$	1/2	1/2	**2**	**1**
	$e_{\mathrm{R},i}$	$e_\mathrm{R},\, \mu_\mathrm{R},\, \tau_\mathrm{R}$	1/2	−1	**1**	**1**
Gauge Fields	$\mathcal{B}$	$\mathcal{B}$	1	0	**1**	**1**
	$\mathcal{W}$	$(\mathcal{W}_1,\, \mathcal{W}_2,\, \mathcal{W}_3)$	1	0	**3**	**1**
	g	g	1	0	**1**	**8**
Higgs Field	ϕ	$(\phi^+,\, \phi^0)$	0	1/2	**2**	**1**

[3]'Ordinary' to distinguish from dark matter, for example.

Table 1.2: The particle content of the SM after the process of electroweak symmetry breaking.

	Physical Field	Q	Coupling	Mass [GeV]
Quarks	u, c, t	$2/3$	$(y_i =)\ 1\times10^{-5}$, 7×10^{-3}, 1	2×10^{-3}, 1.27, 173
	d, s, b	$-1/3$	$(y_i =)\ 3\times10^{-5}$, 5×10^{-4}, 0.02	4×10^{-4}, 0.10, 4.18
Leptons	e, μ, τ	-1	$(y_i =)\ 3\times10^{-7}$, 6×10^{-4}, 0.01	5×10^{-4}, 0.106, 1.777
	ν_e, ν_μ, ν_τ	0	–	–
Bosons	γ	0	$\alpha_{\mathrm{EM}} \simeq 1/137$	0
	$\mathcal{Z}$	0	$\sin\theta_W \simeq 0.5$	91.2
	$(\mathcal{W}^+, \mathcal{W}^-)$	$(+1, -1)$	$\mathcal{V}_{\mathrm{CKM}}$	80.4
	g	0	$\alpha_s \simeq 0.1$	0
Higgs	h	0	λ, μ	125.09

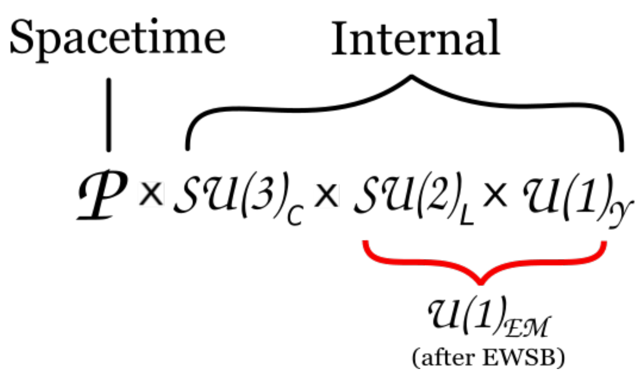

Figure 1.1: Spacetime and internal gauge structure of the SM. $\mathcal{P}$ refers to the Poincaré symmetry. $\mathcal{SU}(3)_c$ refers to the $\mathcal{SU}(3)$ symmetry of the color sector of QCD, $\mathcal{SU}(2)_L$ refers to the left-handed chiral symmetry of the weak interaction, and $\mathcal{U}(1)_Y$ refers to the hypercharge symmetry group of the electroweak interaction. After spontaneous symmetry breaking due to the Higgs mechanism, the $\mathcal{SU}(2)_L\times\ \mathcal{U}(1)_Y$ symmetry reduces to the $\mathcal{U}(1)_{EM}$ symmetry of electromagnetism.

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