THE STANDARD MODEL AND BEYOND:
A descriptive account of fundamental particles
and the quest for the unification of their interactions.

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Abstract

In the last three decades, significant progress has been made in the identification of fundamental particles and the unification of their interactions. This remarkable result is summarized by what is confidently called the Standard Model (SM). This paper presents a descriptive account of the Standard Model and its possible extensions. According to SM, all matter in the universe is made up of a dozen fermions—six quarks and six leptons. The quarks and leptons interact by exchanging a dozen gauge (spin—one) bosons—eight gluons and four electroweak bosons. The Standard Model provides a framework for the unification of the electroweak and strong nuclear forces. A major deficiency of the Standard Model is its exclusion of gravity. The ultimate goal of high energy physics is to unify all the fundamental interactions—gravity, electroweak, and the strong nuclear—into one. This will be equivalent to having a complete theory of everything (TOE). Currently, a contender for a TOE is the so called superstring theory. The theoretical extensions of the Standard Model and the experimental tests of their predictions is likely to engage high energy physicists of the 21st century.

1   HISTORICAL INTRODUCTION

> Our job in physics is to see things simply, to understand a great many complicated phenomena in a unified way, in terms of a few simple principles. *Steven Weinberg* [1]

The development of the Standard Model of particle physics may be the best example for the major goal of physics—simplification and uni-

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[1] S. Weinberg, *Rev. of Mod. Phys.*, "Conceptual Foundations of the Unified Theory of Weak and Electromagnetic Interactions", *52*, 515 (1980). This is the first sentence of his Nobel lecture.

fication of seemingly diverse and complicated natural phenomena. The Standard Model can account for all atomic, nuclear, and subnuclear phenomena in terms of a dozen fermions and a dozen bosons. Once the model is extended to include gravity, it will be possible, at least in principle, to explain all phenomena in the universe as a consequence of a single fundamental interaction. i.e., One will have a theory of everything (TOE). To appreciate the Standard Model, we need to start with a brief historical background of the four (three after 1967) fundamental forces - Gravity, Electromagnetism, the Weak Nuclear force and the Strong Nuclear force.

1.1   Gravity

The first fundamental force (interaction) to be defined accurately was gravity. This was accomplished by Isaac Newton in the 17th century when he stated his universal gravitational law in his *Principa*. Using his law, Newton was able to show that the force of gravity was responsible for motions of planets around the sun as well as for projectile motion on the earth's surface. This was a revolutionary achievement since celestial and terrestrial motions were believed to be caused by two different forces[2] His gravitational law was refined by Albert Einstein in 1916 (almost three centuries later). According to Einstein's general theory of relativity, gravity results form the curvature of space-time due to the presence of mass (or energy). There is now a concerted effort to develop the quantum theory of gravity. In the quantum theory formalism, the gravitational interaction is a consequence of the exchange of gravitons -a massless particle with

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[2]Before Newton. it was believed that heavenly bodies were governed by celestial gravity and free fall and projectile motion on earth were caused by terrestrial gravity.

spin $= 2$. Figure 1a shows a 2nd order Feynman diagram of two masses m_1 and m_2 interacting via a graviton (Γ) exchange.

1.2   Electromagnetism

Prior to the 18th century, magnetic and electrical forces were regarded as unrelated entities. After Oersted (1819) discovered by accident that a current carrying wire deflected a magnetic compass needle, a series of experiments in the 1820s, by Faraday and independently by Henry showed a change in a magnetic field creates an electric field. In addition, Ampère was able to conclude that an electric current loop of molecular (atomic) size was the basis for all magnetism. The intimate relationship between electric and magnetic forces culminated in the development of electromagnetic theory by Clerk Maxwell in 1879. Maxwell's electromagnetic theory provides a complete unification of electricity and magnetism–electromagnetism. This is the first example of a unification of forces. At any point in space a change in electric field (force per unit charge) is compensated force by a corresponding change in magnetic field. This is characteristic of vector fields called gauge fields were local symmetry is preserved via a compensating change in the field components. A relativistic quantum theory (quantum field theory) version of electromagnetic theory was developed mainly by Feynman, Schwinger, and Tomonaga in the 1940s. It is called quantum electrodynamics (QED). It is a theory unprecedented for its precise determination of observable quantities. Besides being the first example of unification of forces and a prototype gauge theory, electromagnetism is the interaction responsible for all atomic, molecular, and hence biochemical phenomena. In the language of quantum field theory, the electromag-

netic interaction is mediated by a massless gauge (spin–one) boson—the photon (γ) and can be represented by the second order (two vertices) Feynman diagram. Figure 1b represents 2nd order Feynman diagram for electron–proton (ep) scattering. Despite the similarity between Figures 1a and 1b, and the similarity between the formulas for the Newton's gravitational law and Coulomb's law, unification of these two forces is still a difficult task. Einstein devoted his last thirty years to unify these two forces without much success. Now, superstring theory is a contender for unifying all the forces.

1.3   The Weak Nuclear Force

In 1930, Pauli postulated that a massless spin-1/2 particle called the neutrino [3] must accompany the emission of the β particle by the nucleus (more specifically by the neutron) if energy, momentum, and spin statistics are to be conserved, Four years later, Fermi (1934) developed the first quantum theory of weak interaction. This is known in the literature as the four–Fermi interaction. As shown in Figure 2, the interaction is represented by a product of four fields at a single vertex (a point). Fermi's theory is still a good approximation (up to 100 GeV). According to Heisenberg's uncertainty principle, a point interaction implies the exchange of a particle of infinite mass. This was considered unrealistic and was later remedied by Klein (1938) who introduced heavy quanta of spin-one (now known as $W^{\pm}$ and Z° bosons). Figures 2a and 2b display Feynman diagrams for β decay as a four-Fermi (point interaction) and as a W bosons exchange

interactions.

1.4   The Strong Nuclear Force

The neutron was discovered in 1932. This meant that the nucleus is made up of protons and neutrons (nucleons). Using the then known forces, primarily the electromagnetic force, it was impossible to account for the stability of nuclei. The electromagnetic force would, in fact, push protons violently apart. This paved the way for Yukawa (1935) to suggest a short ranged strong nuclear force. The strong nuclear force overcomes the electromagnetic repulsion inside the nucleus and binds nuclei. A short ranged force requires the exchange of a massive particle. Yukawa, therefore, predicted the mediator of the strong nuclear force - the pion with a mass of approximately $140 MeV$. It follows from the uncertainty principle ($\Delta t \Delta E \geq \hbar$) that the range of the strong nuclear force ($R \simeq c\Delta t \simeq \frac{\hbar}{m_\pi c}$) is $1.4 \times 10^{-15} m$. Feynman diagrams for the interaction of nucleons via the exchange of pions are shown in Figure 3. Besides the pion(s), many other mesons have been discovered and continue to be discovered. The Yukawa approach has been used to develop two-nucleon interaction models by utilizing various mesons [4] Even

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[3]Neitrinos were detected at the Savannah River Labs in S. Carolina by Cowan and Reines in the 1950s. For a detailed review of the 1950s neutrino search experiments, see Science **203**, 1979.

[4]Yukawa's approach lead to the derivation of a one-pion exchange NN potential (OPEP). Modern NN potentials are based on the exchange of various bosons and hence are called OBEPs. Even though they fit world NN data below 350 MeV very well, they utilize too many parameters (form factors, coupling constants and masses of the bosons). Like the original Yukawa OPEP, OBEPs are based on linear field theory. When the linear pion field theory is replaced by a nonlinear field (a solitary wave) theory, a new class of NN potentials (Solitary Wave Exchange Potentials-SWEPs) emerge. SWEPs fit NN data with a minimum number of parameters. For a sample SWEP and related papers, retrieve the e-print xxx.lanl.gov/abs/nucl-th/9409015.
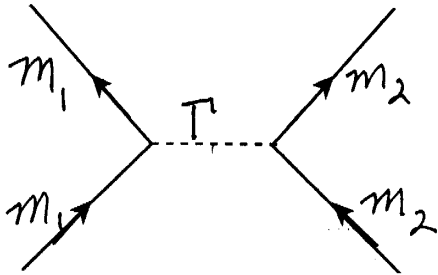
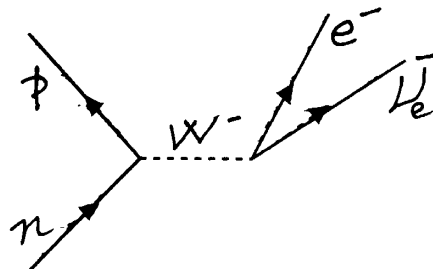**Figure 1a.** 2nd order Feynman diagram for gravitational interaction via a graviton(Γ) exchange.
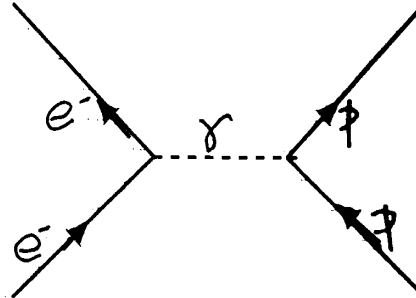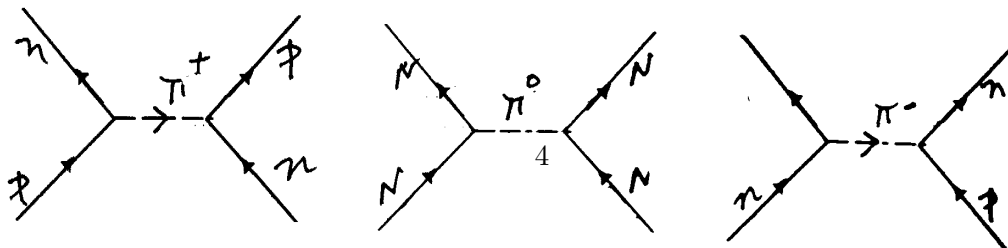

Figure 1b. 2nd order Feynman diagram for ep scattering (E&M interaction) via photon exchange.
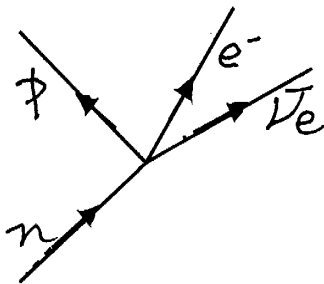
Figure 2a. Four-Fermi interaction for β decay.

Figure 2b. β decay via a W-boson exchange.

Figure 3. 2nd order Feynman diagrams for π^+, π^0 and π^- exchange diagrams.

though the approach is useful at low energy, it is now believed that meson–exchange forces are a manifestation of a more fundamental force called the strong color force. In analogy with quantum electrodynamics (QED), a theory of strong interactions based on quarks and color exchange called quantum chromodynamics (QCD) has been developed.

2 THE STANDARD MODEL

In 1979, exactly a century after the unification of electricity and magnetism by Maxwell, Steven Weinberg, Abdus Salam, and Sheldon Glashow were awarded the Nobel prize for the unification of electromagnetic and weak interactions. The electroweak theory they developed predicted the masses of the $W^{\pm}$, and Z° bosons to be about 80 GeV and 90 GeV respectively [5]. In 1983, physicists at CERN (an European Organization for Nuclear Research) led by Carlo Rubia were able to produce and measure the masses of the W and Z bosons. The measured masses were in complete agreement with the predictions of the electroweak theory. The fact that the electroweak theory was recognized by a Nobel prize before the W and Z bosons were discovered demonstrates the confidence the physics community had for it. The electroweak theory is the central piece of the Standard Model. The incorporation of the symmetry describing the strong force to that representing electroweak theory constitutes the Standard Model of particles and their interactions. A quantitative description of the Standard Model can involve quantum field theory,

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[5]See e.g. Abdus Salam,"Gauge Unification of Fundamental Forces", *Rev. of Mod. Phys.* **52**, 531 (1980). He gives the range of values $M_W \simeq 77 - 84$ GeV and $M_Z \simeq 89 - 95$ GeV.

group theory, and evaluation of complicated integrals related to Feynman diagrams. Our objective in this article is to provide a descriptive account of the development of the Standard Model with emphasis on the unification framework it provides at the moment and the directions it may suggest for its future theoretical extensions and their experimental tests.

2.1 Symmetry

Symmetry plays a central, unifying, and simplifying role in physics. Symmetry implies invariance. All the conservation laws of physics are principles of invariance. For example, translational and rotational invariance lead to the conservation of linear and angular momentum respectively. Symmetry such as that related to translational and rotational invariance is expressed by a set of transformations rules that constitute a mathematical group. Transformations of internal symmetries such as the interchange of color and flavor of quarks can also be described using group theory. "Special Unitary" group represented by a set of 3×3 matrices called SU(3), were used to describe the symmetry of three-quark (uds) flavors. SU(3) is mow used in QCD to represent the symmetry of three-quark colors(RGB). Similarly, SU(2) can be used to describe isospin doublets that interact via the weak interaction. The simplest group is a one-dimensional unitarity group called U(1. It is the symmetry associated with QED. QED involves one gauge boson the photon (γ) and a conserved quantity—the total electrical charge (Q). U(1) is analogous to the symmetry exhibited by a circle rotating on an axis perpendicular to its center. In the language of group theory, the product $SU(3) \times SU(2) \times U(1)$, represents the underlying symmetry of the Standard Model. This is equiv-

alent to saying that the Standard Model incorporates the electroweak theory that is represented by $SU(2) \times U1)$ and QCD which is represented by $SU(3)$.

2.2 Constituents and Mediators of the Standard Model

According to the Standard Model, all matter in the universe is made up of a dozen fermions— six quarks (u, d, s, c, b, t) and six leptons $(e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau)$ that come paired up as doublets of three generations. For each quark flavor there are three colors (red, green [6], and blue). All the quarks and lepton are fermions. i.e., they have spin $=1/2$. Particles with integral spin are called bosons. In particular those with spin $= 1$ are called gauge bosons and those with spin $= 0$ are called scalars. The Standard Model requires the W^+, W^-, Z, and γ spin- one or gauge bosons to mediate the electroweak force and eight gluons—massless gauge bosons that are color anticolor bound states. The constituent particles of the Standard Model and some of their properties are listed in Table 1. The gauge bosons and the forces they mediate are listed in Table 2. Gravity is included for completeness even though it is not part of the Standard Model.

2.3 Unification of the Electromagnetic and Weak Forces.

The grouping of quarks and leptons into pairs of three generations suggests that the quarks and leptons of each generation are weak isospin doublets in analogy with the fact that the proton and

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[6]Some authors, prefer yellow to green. The physics is not affected by this. However, most authors are using the primary colors.

neutron are isospin doublets that are indistinguishable by the strong nuclear force. An isospin group with two members satisfies a symmetry representation—matrix theory called SU(2). SU stand for "Special Unitary". In general we can have SU(N) for N - multiplets. For any SU(N) with $N > 1$ there are $N^2 - 1$ gauge bosons. Consequently, for the weakly interacting weak isospin group SU(2), there must be three gauge bosons. Tentatively these can be identified as the weak isovector triplet - W^+, W^-, and W° bosons. In the 1960s Glashow, Salam, and Weinberg (GSW) were able to unify the weak interaction with the electromagnetic interaction by combining the SU(2) weak isospin group with the U(1) singlet that represents QED. The product $SU(2) \times U(1)$ leads to electroweak theory. If the electroweak theory based on $SU(2) \times U(1)$ is to have perfect symmetry the electroweak isospin triplets —the W bosons— and the electroweak singlet—the photon, must have equal mass. Since the photon has zero mass, this would mean the W bosons will be required to have zero masses as well. However, it was clear from the outset that the weak interaction has an extremely short range $R \simeq 10^{-18} m$. This implies masses of W that is of the order of 100 GeV. As it stands, the $SU(2) \times U(1)$ symmetry is badly broken and requires some justification. The developers of the electroweak theory start with four massless gauge bosons - the triplets W^+, W^-, W° and a B°—an isospin singlet. This would provide a perfect symmetry at very high energy (at $E \geq 100 GeV$) or equivalently at very high temperatures ($10^{15} K$). At lower energies or temperatures, a phase transition occurs and the symmetry is broken (lost or hidden). As a result of the spontaneously broken symmetry, the $W^\pm$ obtain mass and the W° and B° mix and yield the massive Z° boson and the massless photon

Constituent Particles of the Standard Model

Table 1. Quarks and Leptons come in three generations of doublets. Each quark has three possible colors red (R), blue(B), green(G). The leptons are colorless. For each quark and lepton there is a corresponding antiquark and antilepton. The quark masses given correspond to approximate rest mass energy of quarks confined in hadrons. For example, the u or d quark mass is one-third that of the nucleon mass and the c quark mass is one-half of the J/ψ meson mass. (Masses as low as 4 MeV and 7 MeV for the u and d quarks respectively are given by some authors.) Since free quarks have not been observed, quark mass estimates are somewhat uncertain.

Generation	Quarks		Leptons	
First	u (up)	d (down)	e (electron)	ν_e
Mass	330 MeV	333 MeV	0.511 MeV	< 15 eV
Second	c (charmed)	s(strange)	μ (muon)	ν_μ
Mass	1.5 GeV	550 MeV	107 MeV	< 0.6 MeV
Third	t (top)	b (bottom)	τ (tau)	ν_τ
Mass	176 GeV	5 GeV	1784 MeV	< 250 MeV
Charge	$+2e/3$	$-e/3$	$-e$	0
Color	R G B	R G B	colorless	colorless

Table 1: Constituent particles of the Standard Model—quarks and leptons.

Comparison of Fundamental Forces

Table 2. A comparison of the range, relative strength, and some properties of mediators of the fundamental forces. All the given values, except spin, are approximate. Gm_p^2 represent the gravitational strength. G is the Newtonian constant and m_p is the proton mass. $\alpha \simeq \frac{1}{137}$ characterizes the electromagnetic strength. $G_F m_p^2$, the product of four–fermion coupling and square of the proton mass is a measure of the weak force strength. $\alpha_s \simeq 1$ is the color force strength.

Force	Range	Strength	Boson	Mass (GeV)	Spin
Gravity	∞	10^{-38}	graviton	0	2
E. M.	∞	10^{-2}	photon	0	1
Weak	$< 10^{-18}m$	10^{-5}	$W^\pm, Z^\circ$	80, 90	1
Strong	$< 10^{-15}m$	1	gluons	0	1

Table 2: Fundamental forces—range, mediators, and strength.

(γ).

Familiar examples of spontaneously broken symmetry are the phase transition that occurs when water freezes to ice below $0°C$ and when a red hot bar–shaped ferromagnet regains its magnetism after it is cooled. Water exhibits more symmetry than ice and the hot iron bar magnet has no polarity and hence no preferred orientation in space. The loss of its magnetism makes it symmetrical. These two, relatively familiar, examples require exchange of thermal energy with their environment to undergo phase transition. One can thus ask what environmental factors affect the gauge boson of the electroweak force. It is believed that the W and Z bosons obtain their mass form Higgs scalar bosons (suggested by peter Higgs in 1963). At the energy ranges where perfect $SU(2) \times U(1)$ is prevalent a Higgs isospin doublet $(H^+, H°)$ and its antiparticles $(H^-, \bar{H}°)$ are supposed to exist. The Higgs scalar bosons generate mass due to their mutual self interaction. When a phase transition or spontaneous symmetry breaking occurs the masses generated by the $H^\pm$ pair is absorbed by the $W^\pm$ bosons and part of the mass from the $H°\bar{H}°$ pair is used by the $Z°$ boson. Since the photon emerges massless, sufficient mass is available for a free $H°$ boson. A massive neutral Higgs boson ($H°$) should, therefore, be available for observation in future supercolliders. The search for the neutral Higgs boson is likely to be illusive. Unlike the W and Z bosons its mass is not constrained by theory. An important parameter introduced by the mixing of the $W°$ and $B°$ bosons is the θ_W—the Weinberg mixing angle. This angle relates the masses of the W and Z bosons as well as the electromagnetic (e), charged weak (g), and neutral weak (g') couplings.

A summary of these important relations is given below without proof: [7]

$$M_{W^\pm} = \frac{37.3 GeV}{\sin \theta_W}$$

$$M_{Z°} = \frac{M_{W^\pm}}{\cos \theta_W}$$

$$\sqrt{1 + \frac{g'^2}{g^2}} = \frac{1}{\cos \theta_W}.$$

The constant 37.3 GeV above is related to the known values – electron charge (e) and the four-Fermi coupling constant (G_F). A current experimental value for the Weinberg mixing angle (θ_W) is about $28°$ ($\sin^2 \theta_W \simeq 0.22$). Using the above relations one can estimate the $M_{W^\pm}$ and the $M_{Z°}$ to be about $80 GeV$ and $90 GeV$ respectively. As shown in the above equations, these predictions are sensitive to the mixing angle value.

2.4 Experimental Detection of the $W^\pm$ and $Z°$ bosons

Two groups (known as UA1 and UA2) of international physicists totaling about 200 detected the W boson in January 1983 at CERN in Europe. A few months later, the same group(s) discovered the Z boson as well. It was impressive that the masses of these bosons were as predicted by the GSW theory. The leaders of these groups—Carlo Rubia and Simon van der Meer—received a Nobel prize for their remarkable achievement. Their work involved the modification of a Super Proton Synchrotron (SpS) at CERN in to a Super Proton Antiproton Synchrotron (S$p\bar{p}$S)[8] The

[7]For derivations and a list of references, see e.g. H. Frauenfelder and E. M. Henely, *Subatomic Physics*, 2nd ed. (1991).

[8]For details, see D. B. Cline, Carlo Rubia and S. van der Meer, *Sci. American*, March 1982. See also the Nobel

S$p\bar{p}$S enabled them to conduct a $p\bar{p}$ head on collision with energies of about 270 GeV per each beam. i.e., A total of 540 GeV per collision. This provides sufficient energy for the $W^{\pm}$ and Z° to be produced in the reactions:

$$p + \bar{p} \longrightarrow W^{\pm} + X$$

$$p + \bar{p} \longrightarrow Z^{\circ} + X$$

The W and Z produced by the above reactions immediately decay as follows:

$$W^{\pm} \longrightarrow e^{\pm} + \nu_e(\bar{\nu}_e)$$

$$Z^{\circ} \longrightarrow e^- + e^+$$

Feynman diagrams for the above reaction are shown in Figure 4. The lifetime of the W and Z bosons is about 10^{-24} seconds. The $W^{\pm}$ can decay into $e^+\nu_e$ or $e^-\bar{\nu}_e$ and the Z° into e^-e^+ pairs. The decay products fly away opposite to each other (conservation of momentum dictates this) in a direction that is transverse to the beam directions while the fragments ($X = \ldots$) disperse in the beam directions. The masses of the W and Z bosons can be calculated from the momentum and energy of the decay products. Figure 5 shows a lego plot of the energy deposited in a detector when a Z° boson decays in to an electron (e^-) and a positron (e^+) pair.

2.5 The Unification of the Strong Color Force and the Electroweak Force

The discovery of the W and Z bosons is a very strong confirmation of the electroweak theory developed by Glashow, Salam, and Weinberg. The

lectures By C. Rubia and S. van der Meer, *Rev. of Mod. Phys.* **57**, 689 and 699 (1985).

GSW theory also predicts a free neutral Higgs scalar meson that is still at large. So far the GSW theory is consistent with all available data. A discovery of the Higgs boson will just be the final touch it needs to be completely on a firm ground. In parallel with the GSW theory, there have been developments is quantum chromodynamics (QCD). There is now evidence, albeit circumstantial, for six quark flavors. The top quark has recently (1994) been detected or produced at Fermi National Lab. The six flavors of quark come in thee generations of weak isospin doublets. It was this property that enabled GSW to come up with the $SU(2) \times U(1)$ symmetry for electroweak theory. Quarks come in three colors. This immediately suggests the possibility of SU(3) symmetry based on the color multiples. The SU(3) color symmetry will be exact since the three colored quarks of each flavor have the same mass. The SU(3) symmetry of colored quarks would automatically require eight ($3^2 - 1 = 8$) gauge bosons. These are the eight gluons made of color anticolor quark pairs. The construction of gluons is identical to the that of obtaining meson multiplets using quark antiquark pairs. The gluons are responsible for mediating the strong color force that binds hadrons [baryons are bound state of three quarks (qqq states) and bosons are bound states of quarks antiquark ($q\bar{q}$) pairs]. The hadrons are color singlets. A readable account of colored quarks and gluons is given by Sheldon Glashow [9].

The Standard Model results when the electroweak theory group represented by $SU(2) \times U(1)$ is extended to include the SU(3) colored quark group. This is accomplished by multiplying the matrices representing QCD and elec-

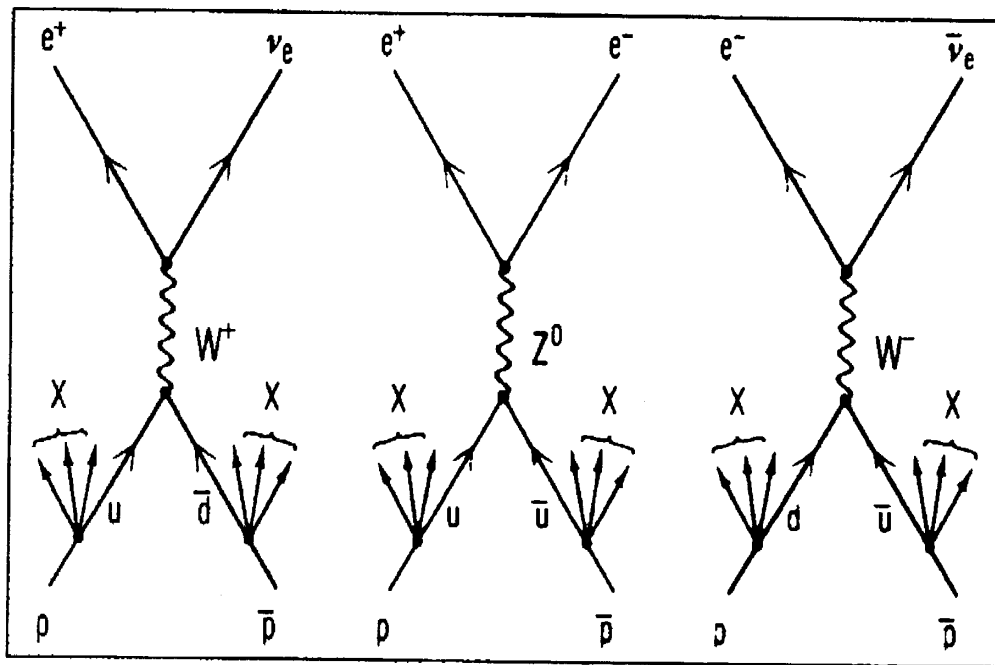[9]S. Glashow,"Quarks With Color and Flavor", *Sci. American*, Oct. 1976.

Fig. 4 Second order $p\bar{p}$ collision Feynman diagrams for the production of W and Z bosons and their decay products.
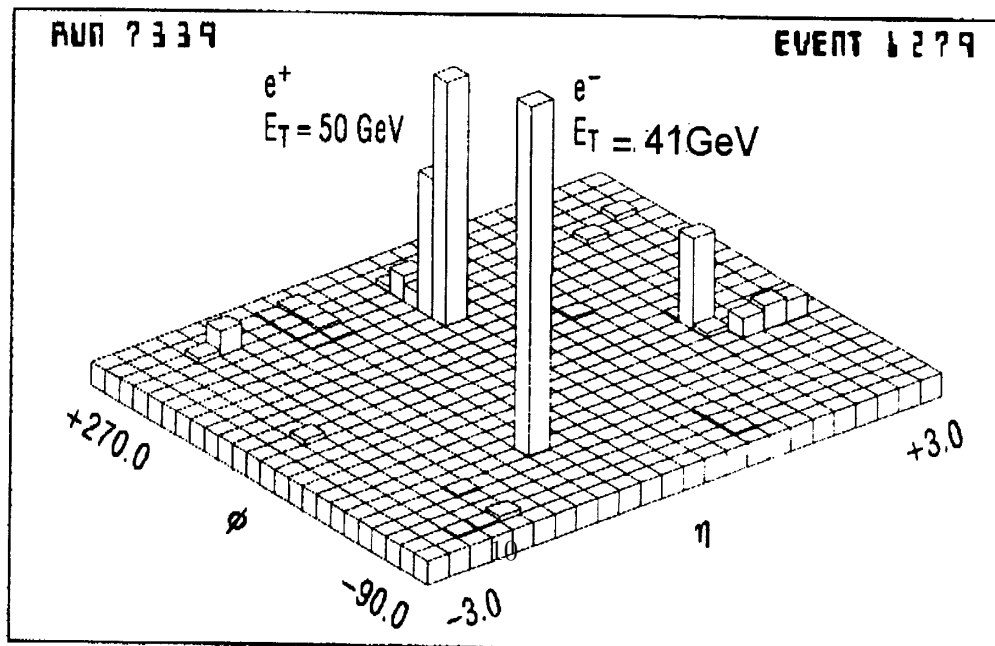

Fig. 5 Energy deposited by the decay of Z^0 in to an electron (e^-) and a positron (e^+) pair after a $p\bar{p}$ collision. ϕ and η are angles in the detector. Adopted from: G. Arnison et al. (UA1 collaboration), Phys. Lett. **126B** 398 (1983).

troweak symmetry—$SU(3) \times SU(2) \times U(1)$. The Standard Model can account for all hadronic (strong interaction) and electroweak phenomena. Meson exchange effects that are still useful in describing low energy nuclear phenomena are residual effects of the strong color force in the same way that molecular forces are consequences of the electromagnetic force. The only fundamental force missing in the picture portrayed by the Standard Model is the gravitational force. The extension of the Standard Model to include the gravitational interaction is an ambitious task. It has recently generated a flurry of activity in theoretical physics. This article will only mention the basic ideas behind these frontier areas of research.

3 BEYOND THE STANDARD MODEL

The $SU(3) \times SU(2) \times U(1)$ gauge theory with three families is certainly a good beginning, not to accept but to attack, extend, and exploit. *Shelodon Lee Glashow* [10]

The Standard Model which is based on $SU(3) \times SU(2) \times U(1)$ symmetry provides a foundation for grander, more inclusive, and, consequently, more speculative unification schemes. Despite its impressive success, the Standard Model excludes gravity. In the Standard Model, the mass differences of the three generations of quarks and the Weinberg angle are parameters that are determined by experiment.

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[10]S. Glashow,"Towards a Unified Theory: Threads in a Tapestry", *Rev. of Mod. Phys,52*, 543, (1980). Nobel lecture.

3.1 Grand Unified Theories (GUTs)

One way to extend the Standard Model and unify its coupling constants (g, g' and e) is to regard the two lepton doublets in each generation as additional indices of color. This results in SU(5) symmetry. Even though the originators of this idea are Glashow and Georgi (1974), varieties of SU(5) based unification theories exist. They are called GUTs (grand unified theories). SU(5) symmetry is supposed to bring quarks and leptons into a single family. It also suggests $(5^2 - 1 = 24)$ two dozen gauge bosons. The Standard Model accounts for half of them. The additional dozen are called X and Y gauge bosons. They carry charges of $\pm 4e/3$ and $\pm e/3$. These super heavy (compared to W and Z) bosons are rendered massive via a spontaneous symmetry breaking that takes place at about 10^{14} GeV (10^{27} K). These energies and temperatures correspond to situations that existed 10^{-33} seconds after the universe was created by a "a hot big bang". It is doubtful, therefore, that they can be achieved in a terrestrial collider of the future[11]. Thus, the X and Y bosons predicted by SU(5) based GUTs may never be observed directly. GUTs predict proton decay with a life time of 10^{30} to 10^{32} years.

Observation of a life time of the order of 10^{30} years may sound ridiculous when the age of the universe is about 2×10^{10} years. However, if one starts with 10^{30} or more protons (about 4000 kg, 4 tonnes, of matter), there is a probability that one of the protons will decay within the first year. Observations of huge (about three

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[11]The SSC was expected to attain a 20,000 GeV (20 TeV) of beam energy. The total center of mass energy when two protons collide will be 40 TeV This is 20 times the energy available at present. For details on the SSC, see e.g.; J. D. Jackson et al. *Sci. American*, March 1986.

thousand tonnes) underground pools of water indicate that protons are much more stable than the GUTs predict. GUTs also predict magnetic monopoles with mass of the order 10^{16} GeV. Since they are stable, they should be observed as remnants of the phase transition that produces the X and Y bosons. Neither of these prediction have materialized. However, GUTs yield reasonable values for the Weinberg angle ($\sin^2 \theta_W \simeq 0.21$) and the bottom quark mass (5 GeV). Their major deficiency is the neglect of gravity.

3.2 Subquarks

The Standard Model requires: six flavors of quarks and antiquarks each with three colors; six leptons and antileptons; a dozen gauge bosons; and four Higgs bosons. i.e. a total of about sixty four particles. Guts add a dozen gauge bosons extending the number of fundamental particles to at least seventy six. This presents a dilemma. Unification of fundamental interactions seems to come at the cost of increasing the number of fundamental particles. The desired goal is to unify the forces and build all matter in terms of few fundamental entities. One way of reducing the number of particles is to introduce subquarks or techniquarks that serve as building blocks of quarks and leptons. A simple and economical model developed independently by Harari in Israel and Shupe in the U.S.[12], requires only two fundamental fermions and their antiparticles to account for all the leptons and quarks of the Standard Model. This model introduces hypercolor and hence involves a more fundamental force than the strong color force. Similarly, techniquark based model utilize technicolor

[12]H. Harari,"The Structure of Quarks and Leptons", *Sci. American*, April, 1983.

forces. Experimental indication for substrata of leptons and/or quarks is currently non existent. No body knows, however, what the next generation of super colliders may unfold. Could it be that leptons and quarks have structure?

3.3 The Planck Scale and Quantum Gravity

Gravity, the oldest known fundamental force, is also the last to be included in a unification scheme. An attempt by Einstein, to unify electromagnetism and gravitational forces was unsuccessful. Part of the reason for the neglect of (or difficulty in including) gravity in particle interaction is due to the fact that gravity is too feeble to affect elementary particles. e.g. The ratio of the gravitational to electric force an electron feels due to the presence of a proton is of the order 10^{-40}. In QED, the electromagnetic strength is characterized by the dimensionless constant— the fine structure constant:

$$\alpha_f = \frac{ke^2}{\hbar c} \simeq \frac{1}{137}.$$

Where $k = \frac{1}{4\pi\varepsilon_0}$ is the Coulomb constant. Similarly, a fine structure constant for quantum gravity is defined as:

$$\alpha_g = \frac{GM_P^2}{\hbar c} \simeq 1$$

Where, G is the universal gravitational constant and $M_P \simeq 10^{19}$ GeV , is known as the Planck mass. Using this mass in Heisenberg's uncertainty principle yields: the Planck length, $\ell_P \simeq 10^{-35}$ meters, the Planck time and $\tau_P \simeq 10^{-43}$ seconds. At the Planck scale gravitational interactions are strong and hence non negligible and hence must be included in particle physics. It becomes necessary, therefore, to introduce a new

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grand symmetry that provides the framework for unification of all the fundamental forces including gravity.

3.4   Supersymmetry—SUSY

The symmetry that extends the Standard Model (or GUTs) so that quantum gravity is included is called supersymmetry (SUSY). SUSY is relevant at the Planck scale. To achieve a complete unification of all the forces, it postulates that for every fermion there is an associated boson and vice versa. i.e., for every quark there is an squark, for every lepton there is a slepton (e.g., an electron should have a SUSY partner called selectron). Table 3. lists particles of the Standard Model and their SUSY partners (sparticles). Introduction of sparticles doubles the number of fundamental particles. In addition, SUSY requires a total of 496 gauge bosons. The statement that for every particle there is an sparticle is analogous to saying—for every particle there is antiparticle. Sparticles are supposed to play an important role in canceling divergences that result when calculations of interaction amplitudes are attempted at Planck scales. e.g., divergences that arise due to graviton exchange are taken care off by including the exchange of a gravitino (the SUSY partner of graviton). At a time (or energy scale) when SUSY was an exact symmetry particles and sparticles would all have the same mass (possibly zero mass). Currently, many of the remnants of these sparticles could be too massive to detect. There should be some that are detectable. Thus far, no sparticle candidate has been observed.

symmetry such as SU(5) with space-time invariance (local gauge symmetry). Space-time invariance is the province of general theory of relativity. The local gauge component of SUSY is called supergravity (SUGRA)[13] It is a quantum theory of gravity in ten dimensions (9 space + 1 time). The extra six spatial dimensions are supposed to be curled up (compactified) to a region of the order of Planck length. [14].

3.5   Superstring Theory—A Theory of Everything (TOE).

In an attempt to unify everything SUSY more than doubles the number of fundamental particles. Escalation of the number of fundamental particles is contrary to the goals of theoretical physics. A tentatively promising approach is the combination of an old string theory [15] In superstring theory, the fundamental blocks of matter are not particles (points) but line segments called superstrings that are of the order of Planck length. Superstrings come in two forms—open and closed. Open superstrings have free ends to which conserved quantities such as charge can be attached. Closed superstrings are loops. Spin - 1 gauge bosons are vibrational modes of open superstrings. Spinning super-

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[13]For a readable account of supergravity see: D. Z. Freeman and P. van Nieuwenhuizen, "Supergravity and the Unification of the Laws of Physics", *Sci. American* Feb. 1978.

[14]The extension of space–time dimensions has its origins in the 1920s when first Kaluza and later Klein suggested adding a hidden fifth dimension could facilitate the unification of electromagnetism and gravity. Such theories are now called Kaluza-Klein theories.

[15]String theory was developed in the 1960s to explain hadron spectra. It was later given up in favor of the quark model. For a non mathematical discussion of superstring theory , see e.g.,: M. B. Green, "Superstrings",*Sci. American*, Sept. 1986 and the book by Brian Green: *The Elegant Universe, Hidden Dimensions, and the Quest for the Ultimate Theory. W. W. Norton 1999.* Live webcasts from CERN and guided tours from Fermi Lab on SM and beyond as well as a variety of superstring websites are available on the Internet.

| Particles and their SUSY Partners			
Table 3. A list of constituent particles and gauge bosons of the Standard Model with their supersymmetric partners. For completeness, the graviton (spin = 2) has the SUSY partner gravitino (spin=$\frac{3}{2}$).			
Constituent Particles		Gauge Bosons	
Spin$\frac{1}{2}$	Spin 0	Spin 1	Spin $\frac{1}{2}$
quark(q)	squark($\tilde{q}$)	photon(γ)	photino($\tilde{\gamma}$)
lepton(l)	slepton($\tilde{l}$)	W, Z, bosons	wino($\tilde{W}$), zino($\tilde{Z}$)
higgisimo($\tilde{\phi}$)	higgs(ϕ)	gluon(g)	gluino($\tilde{g}$)

Table 3: Particles and sparticles.

strings may be equivalent to fermions. Superstrings can join and form closed ones. A graviton arises as a vibrational mode of a closed superstring. In general, the fundamental particles can be regarded as a spectra of the excitations of the superstrings. The tension (mass/length) of the superstrings sets the vibrational modes. Superstrings have a rich structure and many excitational modes. They have lead to a variety of possible theories. All versions unify the fundamental forces, they provide a means for generating the fundamental constituent particles as well as the gauge bosons (including the illusive graviton) of the standard model and beyond— they are the theory of everything (TOE). Without the usual interplay between experiment and theory, the only check we have on superstring theories is to demand they be internally consistent. TOEs are supposed to be transparent only at the planck scale. i.e. at a times of the order of 10^{-43} seconds after the "hot big bang". Today we live at a time that is three broken symmetries (phase changes) removed from the era of TOE. At the extremely high energy limit, the study of the very small, particle physics, and of the very large—cosmology have merged. Early cosmology has become synonymous with high energy physics. Superstring theory, though highly speculative, has generated a lot interest and activity among high energy physicists, astrophysicists, and mathematicians. Even though a large number of superstring theories' predictions may never be accessible to any man-made super collider, there could be some cosmic remnants and less massive (mass of the order of 10 TeV or less) sparticles waiting to be discovered. It would also exciting if some light sparticles show up. The discovery of an sparticle would make SUSY, SUGRA, superstring theory etc. credible and more exciting It is not clear when one can expect to have a unified theory (TOE). Even when we have a Theory of Every thing it does not mean the end of physics. TOEs may not solve for us practical problems. Fundamental issues related to the anticipation of unified theory in the next century and what to expect from it is addressed by S. Weinberg. [16].

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[16]S. Weinberg, "A Unified Physics by 2050?", *Sci. Am, Dec. 1999*
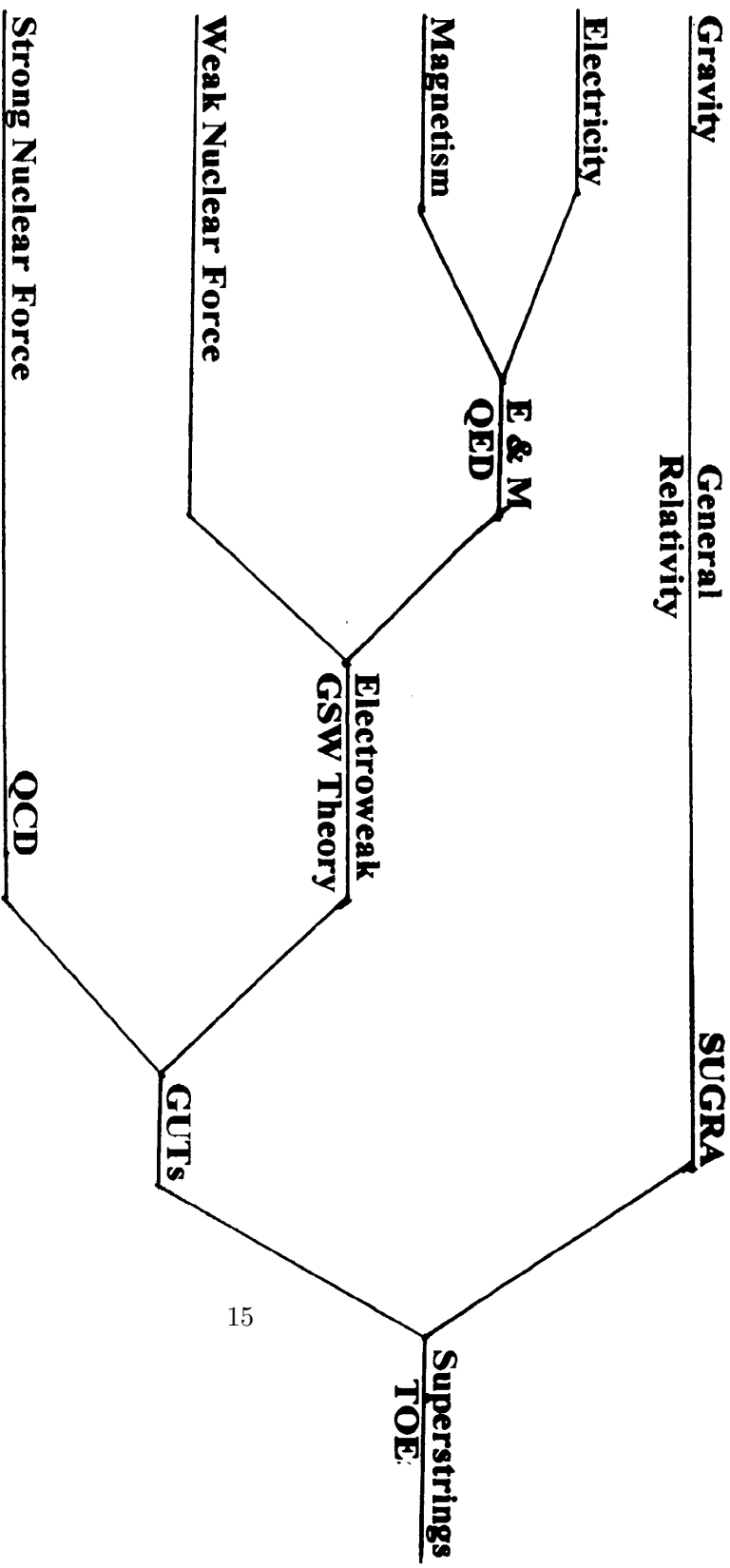
Figure 6: Unification of Fundamental Forces and Theories.

3.6   Summary

The journey physics has taken in the last four centuries and may continue to do so in the next century in the quest for a unified theory–a Theory of Every Thing (TOE)is summarized by the line drawings in Figure 6. Gravity will be the last one to join the Elecroweak and Strong nuclear forces.   Superstring theory promises to unify SUGRA(quantum gravity) with GUTs(a combination of Electoweak (GSW) Theory and QCD). This is supposed to be realized at extremely high energies of the order 10^{19} GeV. Unfortunately, this will not be accessible to any man-made super collider. The interplay between experiment and theory will be lost. To evaluate TOEs, One has to rely on their internal mathematical consistency and their low energy limit predictions. It will not be unreasonable, for example, to expect TOEs to enable us to calculate the seemingly arbitrary parameters of the Standard Model such as the quark and lepton masses.