MOTIVATION FOR SUPERSYMMETRY

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We discuss some of the shortcomings of the Standard Model and provide a phenomenological presentation of supersymmetry. Specifically, we present three reasons why the Standard Model is theoretically flawed: the fine tuning problem, the hierarchy problem, and the spontaneity of electroweak symmetry breaking. We show how Supersymmetry solves these problems and conclude with the construction of the Minimally Supersymmetric Standard Model.[1]

1 The Allure of New Physics

The Standard Model contains several theoretical problems. First, radiative corrections must be made to the scalar Higgs mass. Quartic self-interactions of the Higgs boson, from one loop corrections, generate a quadratically divergent contribution to its mass which must be compensated with a counterterm

$$M_h^2 \sim M_{h0}^2 + \frac{\lambda}{4\pi^2}\Lambda^2 + \delta M_h^2$$

where M_{h0}^2 is the bare mass, λ is the coupling, Λ is a cutoff scale, which in the Standard Model must be of the order of the Planck scale, and δM_h^2 is the compensating term. Unitarity, the requirement that all production cross sections must fall as s^{-1} at energies far above the mass of the produced particle, demands that M_h must be less than around 800 GeV/c^2, which in turn requires that δM_h^2 be adjusted to about one part in 10^{16}. This extreme sensitivity is present at each order in perturbation theory, so one must fine tune the corrections indefinitely; this is known as *the fine tuning problem.*[2]

Second, the Standard Model contains a large scale hierarchy, $M_W \ll M_{Planck}$, which is unstable; small changes at one scale can lead to large variations at the other scale. Usually, large hierarchies are protected by an intervening approximate symmetry; for example, classical QCD scale invariance protects $m_{proton} \ll M_{Planck}$, and chiral symmetry (with $m_e = 0$) protects $m_e \ll M_W$. The Standard Model contains no symmetry which protects $M_W \ll M_{Planck}$ and suggests an additional undiscovered symmetry.

Finally, electroweak symmetry breaking (EWSB) is introduced artificially: the symmetry is spontaneously broken at just the right scale to agree with experiment. The Standard Model contains no hint of the origin of this breaking. Extensions to the Standard Model which try to explain EWSB usually require currently undiscovered particles near the weak scale (~ 100 GeV).

The predictions of the Standard Model have withstood all current precision measurements, indicating the model's validity up to the energies already probed.[a] Occasionally, a result will appear in the literature that seems to favor one extension of the Standard Model over another. Subsequent results usually modify this favoritism back to the bare Standard Model. No matter how experimental results drift with time, the aforementioned theoretical problems with the Standard Model persist, **requiring** new physics, usually at or near the weak scale.

2 Supersymmetry

One way to remove the quadratic divergence in radiative corrections to the Higgs mass is to introduce another field into the Lagrangian. The one-loop corrections to the mass become

$$M_h^2 \sim M_{h0}^2 + \frac{g_F^2}{4\pi^2}\left(\Lambda^2 + m_F^2\right) - \frac{g_S^2}{4\pi^2}\left(\Lambda^2 + m_S^2\right) + \ldots$$

where we have replaced the generic coupling λ with $g_{F,S}$ and included explicitly the mass of the particles responsible for the corrections. The omitted terms either diverge only logarithmically or are uninteresting. To ensure the relative minus sign, one of the fields must obey Fermi-Dirac statistics, while the other must obey Bose-Einstein statistics; thus, for every Dirac particle in the standard model, a scalar partner must exist, and for every boson, a Dirac partner must exist. We combine the two fields into a *superfield* containing particles and their superfield partners, *sparticles*. For example, quarks would partner with a scalar quark, or *squark*. The spin of a sparticle differs by one-half unit from its partner, but otherwise has the same quantum numbers. This symmetry between fermions and bosons is called *Supersymmetry* (SUSY). Table 1 presents the complete SUSY particle spectrum. By examining the above equation, one can see that SUSY models implicitly solve the fine tuning problem, provided $|g_F| = |g_S|$ and $m_F^2 \sim m_S^2$.[b] In addition, SUSY provides an origin for EWSB

[a] But note the recent HERA announcement of an excess.

[b] Exact cancellation occurs when the masses of the partners are equal; an intrinsic feature of unbroken supersymmetry. SUSY must be a broken symmetry, at scale M_{SUSY}, else the electron would have a scalar partner with the same mass and quantum numbers. Attempts

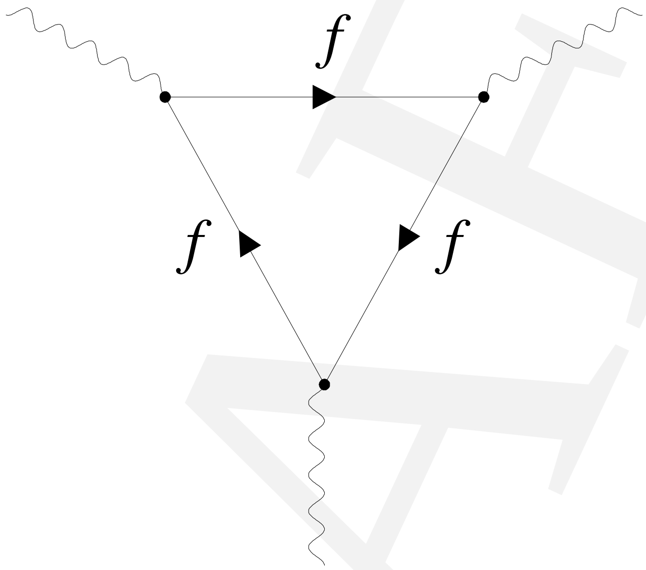

Figure 1: Example of triangle diagram which produces a gauge anomaly. There exists such a diagram for every fermion within a model.

and solves the hierarchy problem by protecting the scale difference with the chiral symmetry of the superfield.[c]

The SUSY extension to the Standard Model which is complete and adds the least number of undiscovered particles is called *minimal SUSY*. To construct minimal SUSY, special attention must be paid to the Higgs sector. The Standard Model contains a single $SU(2)_L$ Higgs doublet consisting of 2 complex scalar fields, requiring 4 real scalar parameters. Three of these 4 degrees of freedom give mass to the W and Z bosons, so the Standard Model contains one physical scalar Higgs. When we add a fermion partner for the Higgs, we revive the problem of triangle *gauge anomalies*.

Figure 1 is an example of a gauge anomaly. Such an interaction exists

to quantify how similar particle and sparticle masses must be result in a general mass limit of about a TeV for sparticles.

[c]A chiral theory is one in which the gauge bosons couple differently to left- and right-handed fermion states.

for every fermion in the Standard Model. Because the left and right fermion couplings are unequal in standard electroweak theory, the individual fermion contributions become infinite in an awkward way that upsets standard renormalization. To free the theory of anomalies, the net contribution of these diagrams must be zero. This is accomplished in the Standard Model by requiring that generations be complete; the contributions from u and d quarks exactly cancel that from the electron.[d]

When we add the fermion partner to the Higgs, the exact cancellation of gauge anomalies is again upset; we must have at least one more fermion to cancel its contribution. Within the framework of SUSY, the minimal option is to add an additional superfield. Therefore, minimal SUSY contains two Higgs doublets instead of a single one as in the Standard Model. Each particle doublet contains two complex elements and thus eight real scalars. Three of these scalars give mass to the W and Z bosons; hence, minimal SUSY contains 5 physical Higgs bosons: two charged, two neutral, and one neutral pseudoscalar.

We introduce a new quantum number, R. $R = +1$ for particles and $R = -1$ for sparticles, and the total R of a state is calculated by multiplying all of the individual particle and sparticle R's. A SUSY model can be classified as R-parity conserving, or R-parity violating.

In all current colliders, the initial state is assumed to only contains particles, so its R value is $+1$; therefore, in R-parity conserving models, the final state must contain an even number of sparticles, usually two. Each SUSY model of this type contains a *Lightest Supersymmetric Particle* (LSP) which cannot decay. Much like neutrinos, the LSPs are assumed neutral and weakly interacting, and they provide a candidate for Cold Dark Matter. The general SUSY interaction of this type can be described

$$\overline{p}p \longrightarrow 2\,\mathrm{LSP} + X$$

where X represents collection of Standard Model particles such as photons or jets from hadronization of quarks. The presence of LSPs in an event is inferred from $\not{E}_T$.

The general SUSY naming convention is to precede a scalar partner's name with an "s", giving us squarks and sleptons generically, and sneutrinos and selectrons specifically.[e] The spin one-half gauge fermions are named by adding

[d] This feature of the Standard Model required the existence of the top quark to complete the third generation.[3] The GIM mechanism also requires complete generations, but for different reasons.

[e] Terms such as "stop squark" are redundant; one should refer to a stop quark, a top squark, or just a stop.

Table 1: The minimal SUSY particle spectrum. The gauginos mix according to charge; hence, charginos are mixtures of charged higgsinos and winos, and neutralinos are mixtures of neutral higgsinos, zinos, and photinos. For the squarks and sleptons we use a subscript (L or R) denoting to which particle chiral state the sparticle is a partner. Alternate notations exist for some sparticles.

Particles		**Sparticles**		
Name	*Symbol*	*Name*	*Symbol*	*Alternate*
gluon	g	gluino	$\widetilde{g}$	
charged higgs W boson	$H^{\pm}$ $W^{\pm}$	charginos	$\widetilde{W}^{\pm}_{1,2}$	$\widetilde{\chi}^{\pm}_{1,2}$, $\widetilde{C}_{1,2}$
light higgs heavy higgs pseudoscalar higgs Z boson photon	h H A Z γ	neutralinos	$\widetilde{Z}^{\pm}_{1-4}$	$\widetilde{\chi}^{0}_{1-4}$, $\widetilde{N}_{1-4}$
graviton	G	gravitino	$\widetilde{G}$	
quarks	$q_{L,R}$	squarks	$\widetilde{q}_{L,R}$	
leptons	$l_{L,R}$, ν_L	sleptons	$\widetilde{l}_{L,R}$, $\widetilde{\nu}_L$	

the suffix "-ino" to the Standard Model name; therefore, the gauginos are called photinos, winos (pronounced wee′nos), zinos (zee′nos), gluinos, and Higgsinos. The electroweak gaugino fields mix according to electromagnetic charge and are more properly referred to as charginos and neutralinos. Finally, the spin 2 graviton superpartner is the spin 3/2 gravitino. Table 1 shows the complete minimal SUSY particle spectrum.[f]

3 Conclusions

We have provided a short introduction into the motivation for Supersymmetry. We have detailed some of the theoretical problems of the Standard Model and presented the construction of the minimal SUSY model. Revisions of this note will commence as required.

[f] While somewhat whimsical, the SUSY naming convention is extremely concise.

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References

1. The information presented is adapted from the introductory materiel contained in "Searches for New Physics at DØ", presented at *The Lake Louise Winter Institute: Particles and the Universe*, Lake Louise, Alberta, Canada, February 1997.
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