Spin beyond Standard Model: Theory

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Abstract. I use spin as a guide through the labyrinth of possibilities and ideas that go beyond the established understanding of the fundamental interactions.

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INTRODUCTION

What is required to define spin are Lorentz-covariant free particles and quantum mechanics. On the other hand, causality (from demanding a Lorentz invariant S-matrix) and the cluster decomposition principle (the requirement that distant experiments yield unrelated results which in relativistic theories naturally leads to the concept of quantum fields) are not necessary. Thus, spin can be considered even outside the framework of a quantum field theory (QFT) — but not conversely — and can serve as a very general organizing principle for the many types of physics beyond the Standard Model (SM) that have been suggested\(^1\) including extra dimensions, strings, and M-theory.

The complete classification of unitary representations of the inhomogeneous Lorentz group according to Wigner [4] is recalled in Table 1. The little group is defined as the subgroup leaving some conveniently chosen "standard" four-momentum, \(k^\mu\), unchanged and gives rise to spin and helicity. Thus, for a massive particle the possible spin states are obtained from the \(SO(3)\) Lie algebra and are consequently identical to those familiar from non-relativistic quantum mechanics. The little group for massless particles is the

| \(p^2\) | \(p_0\) | \(\text{standard } k^\mu\) | \(\text{little group}\) | \(\text{comment}\) |
|---|---|---|---|---|
| \(> 0\) | \(> 0\) | \((M,0,0,0)\) | \(SO(3)\) | massive particle |
| \(> 0\) | \(< 0\) | \(\text{any } M\) | \(SO(3)\) | \(E < 0\) (unphysical) |
| \(= 0\) | \(> 0\) | \((k,k,0,0)\) | \(ISO(2)\) | massless particle |
| \(= 0\) | \(= 0\) | \((0,0,0,0)\) | \(SO(3,1)\) | vacuum (no particles) |
| \(= 0\) | \(< 0\) | \(\text{any } k\) | \(ISO(2)\) | \(E < 0\) (unphysical) |
| \(< 0\) | \(\text{any}\) | \((0,M,0,0)\) | \(SO(2,1)\) | tachyon \(\{|v| > c\}\) |

\(^1\) For tests of the SM see the contributions by Bill Marciano [1] (muon anomalous magnetic moment and CKM unitarity), Yannis Semertzidis [2] (electric dipole moments and \(\mu \to e\) conversion), and Krishna Kumar [3] (polarized electron scattering).
Euclidean group in two dimensions, ISO(2) (generated by two translations and one rotation), and (being non-compact) permits, in general, a continuous parameter ("continuous spin"). One assumes (basically on phenomenological grounds) that physical states are non-trivially represented only with respect to the compact $SO(2) = U(1)$ subgroup, and identifies its "charges" with the helicity, $h$, of the massless particle. The trivial $U(1)$ Lie algebra would allow arbitrary values of $h$, but the topology of $SO(3,1) = SL(2,\mathbb{C})/\mathbb{Z}_2$ can be shown to be that of the doubly connected space $\mathbb{R}^3 \times S^3/\mathbb{Z}_2$, so that the requirement of a globally defined wave function restricts $h$ to integer and half-integer values. Still, Lorentz invariance requires consideration of the entire ISO(2) little group. I will return to this point in the discussion of states with $h \geq 1$.

The spin 0 category includes the (would-be) Nambu-Goldstone bosons of spontaneously broken continuous symmetries, such as Higgs bosons, familons (broken family symmetry), Majorons (broken lepton number conservation), or axions (broken Peccei-Quinn symmetries). Furthermore, there may be radions (graviscalar components of the metric tensor in models with extra spatial dimensions), dilatons (e.g., in string theories), moduli (scalars with flat potential in supersymmetry), inflatons, scalar leptoquarks, and sfermions (scalar superpartners). Spin 1/2 states beyond the SM could be due to a fourth family, right-handed neutrinos, other exotic states (e.g., those needed to cancel anomalies in models with new gauge symmetries), techniquarks from dynamical (strong) symmetry breaking models, or X-inos (fermionic superpartners other than gravitinos). Spin 1 states could be extra $Z'$ or $W'$ bosons or vector leptoquarks (e.g., from Grand Unified Theories). Examples for spin 2 particles are the graviton (predicted by string and M-theory) and its Kaluza-Klein excitations (in models with extra dimensions). A massless particle with spin $> 2$ is not expected to give rise to a long-range force, but the towers of massive string excitations include states with arbitrarily high spins. On the other hand, a massless particle (or massive particle after spontaneous supersymmetry breaking) of spin 3/2 would uniquely point to the gravitino of local supersymmetry (supergravity).
FIGURE 2. Results from Higgs searches at run II of the Tevatron [6]. The meaning of the lines and bands is as in the right panel of Figure 1. Notice, that the right-hand plot is from a slightly larger data set.

**SPIN 0**

The unique fundamental scalar within the SM is the yet to be discovered Higgs boson. Its mass, $M_H$, is constrained from direct (so far negative) searches and from indirect precision analyzes (quantum loop effects). The global fit to all indirect data currently yields $M_H = 89^{+29}_{-22}$ GeV, with a very reasonable goodness of the fit. The $M_H$ constraints as functions of the top quark mass, $m_t$, are shown in Figure 1 for various data sets. As can be seen, these are consistent with each other with the exception of the low energy data which deviate mainly due to the result on deep inelastic neutrino scattering (NuTeV).

LEP 2 (Figure 1) excluded Higgs masses below 114.4 GeV (95% CL), and saw a small but by itself insignificant excess around $M_H = 117$ GeV. An upward fluctuation is also seen for similar $M_H$ values at run II of the Tevatron (Figure 2). The best sensitivity is here for Higgs masses slightly above the threshold for decays into $W$ pairs and thanks to a downward fluctuation values close to $M_H = 170$ GeV could already be ruled out. The combined result of all constraints (direct and indirect) is shown in Figure 3.

Even though the Higgs boson is a SM particle, it may provide clues about new physics. E.g., if one requires that it remains perturbatively coupled up to the fundamental Planck scale, $\kappa_4 \approx 2.4 \times 10^{18}$ GeV, one obtains (in the absence of new physics) the upper limit, $M_H \lesssim 180$ GeV. Likewise, vacuum stability up to $\kappa_4$ implies $M_H \gtrsim 130$ GeV (if one allows a meta-stable vacuum this weakens to $M_H \gtrsim 115$ GeV). In general, one expects $M_H$ to be of the form $M_H^2 = (M_H^0)^2 + c \frac{\kappa_4}{\pi} \kappa_4^2 \ll \kappa_4^2$, and $c = O(1)$ would require a delicate cancellation of the tree and loop terms (the hierarchy problem). The main mission of the LHC is then to find at least one Higgs boson and the new physics providing the solution to the hierarchy problem (ideally) also explaining (i) why the precision data appear to be consistent with the SM with so far no clear indication for new physics, (ii) the nature of the dark matter, and (iii) the baryon asymmetry of the universe.

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2 There is no hierarchy problem for fermions, because chiral symmetry protects massless fermions to acquire masses radiatively, and so the radiative corrections for massive fermions will be no larger than of the order of the chiral symmetry breaking tree mass terms themselves.
One way to address the hierarchy problem is to avoid fundamental scalars altogether. In the original technicolor (TC) idea\,[7,8] (techni)fermions condense through non-Abelian gauge interactions, break electroweak symmetry (EWS), and generate the masses for the W and Z bosons. It is less straightforward to obtain the masses for the SM fermions and extended technicolor gauge interactions are needed. In general, this leads in turn to large flavor changing neutral current effects in conflict with observation. This can be cured by decelerating the running of the TC coupling (walking TC) so as to effectively decouple the extended TC gauge bosons. Another complication is the large $m_t$ value and one considers models of top quark condensation (topcolor). Models in which the EWS breaks solely due to topcolor predict too large an $m_t$ so that one arrives at hybrid models (topcolor assisted TC). One also has to introduce an extra $U(1)'$ gauge symmetry to prevent condensation of the much lighter bottom quarks. This is one of many examples in which a model of EWS breaking predicts a specific massive $Z'$ boson to solve some model building problem. Thus, $Z'$ diagnostics may be an additional analyzing tool for the new physics that breaks EWS. However, models of TC are generally in conflict with the S parameter (Figure 3). Incidentally, the S parameter also constrains a fourth fermion generation and rules it out if mass degenerate ($S = 2/3\pi$). The non-degenerate case is also disfavored and only marginally consistent for specific mass values.

Another way to avoid fundamental scalars is to assume that the Higgs field is composite\,[9]. A modern reincarnation of this idea is Little Higgs Theory\,[10] with a fundamental scale $\Lambda$ of 5 to 10 TeV, and where the Higgs is lighter since it appears as a pseudo-Goldstone boson. In these models the quadratically divergent contributions to $M_H$ are then postponed by one loop order (in some models by two orders). One can also assume that quarks and leptons are composite. This introduces effective contact interactions with an effective scale constrained by LEP 2 to satisfy $\Lambda \gtrsim \mathcal{O}(10\,\text{TeV})$. 

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**FIGURE 3.** Left: Combination of direct and indirect constraints on $M_H$. The red (solid) histogram includes all data while the yellow line shows the result without the Tevatron constraints. The 95% upper limits are also shown, where LEP 2 obtained their 190 GeV upper limit by treating their lower bound as a step function. Right: $1\sigma$ constraints on the parameters S and T (describing gauge boson self-energies) for various data sets and $M_H = 117$ GeV. The 90% allowed regions for all data and three reference values for $M_H$ are also shown. In the SM, $S = T = 0$ (by definition) while in TC models typically $S \gtrsim 1$. 

SPIN 1/2
SPIN 1

In a QFT, a particle with $h = \pm 1$ can produce a long-range $(1/r^2)$ force only if it is coupled to a conserved vector current. This can be traced to the ISO(2) little group mentioned in the introduction and implies the concept of gauge invariance [11]. Extra neutral gauge bosons ($Z'$) can arise from extra $U(1)'$ gauge symmetries as contained, e.g., in the $E_6$ unification group, $E_6 \rightarrow SO(10) \times U(1) \rightarrow SU(5) \times U(1)^2$, or in left-right symmetric models, $SU(2)_L \times SU(2)_R \times U(1) \rightarrow SU(2)_L \times U(1)^2$. The $Z'$ could also be a Kaluza-Klein (KK) excitation (sequential $Z'$), the techni-$\rho$, or the topcolor-$Z'$ mentioned above. The $Z'$ mass, $M_{Z'}$, is constrained to be greater than 1305 GeV in the sequential case (DELPHI) and $M_{Z'} > 630$ to 891 GeV for $E_6$ scenarios (DØ), while electroweak (EW) data limit the mixing angle with the ordinary $Z$ to $< 0.01$. Likewise, mass and mixing of an extra $W'$ are limited, respectively, to $> 1$ TeV (DØ) and $< 0.12$ (OPAL).

SPIN 2

In a QFT, $1/r^2$-forces are produced by an $h = \pm 2$ particle only if it is coupled to the conserved energy-momentum tensor implying invariance under general coordinate transformations [11]. The ultraviolet completion of gravity requires its embedding into structures like string or M-theory whose growing number of known vacua led to the concept of the string landscape [12] and a revival of anthropic reasoning (the multiverse).

String [13] and M-theory [14] predict the existence of extra dimensions (EDs), some of which are conceivably much larger than $\kappa_4^{-1}$. One can consider [15] a factorized $D$-dimensional space, $\mathbb{R}^4 \times M^{D-4}$, where $M$ is a flat space with volume $(2\pi R)^{D-4}$. The $D$-dimensional Planck scale, $\kappa_D$, is identified with the EW scale, and the hierarchy problem appears here as the puzzle why $R^{-1} = \kappa_D(\kappa_D/\kappa_4)^{2/(D-4)} \ll \kappa_D$ (the case $D = 4 + 1$ is excluded from precision studies of Newton’s law). Collider processes such as $e^+e^- \rightarrow \gamma \gamma$ missing energy require $\kappa_D > \mathcal{O}(1 \text{ TeV})$, while astrophysical bounds, $\kappa_D \geq \mathcal{O}(100 \text{ TeV})$, can be avoided in models. An alternative is to introduce a warped 5-dimensional space [16] with metric, $d\mathcal{S}^5 = e^{-\gamma k} \eta_{\mu\nu}dx^\mu dx^\nu - dy^2$, where $k$ is the anti-de-Sitter (AdS) curvature and $0 \leq y \leq \pi R$ the fifth coordinate. The EW scale is here exponentially suppressed ($\sim \kappa_4 e^{-\pi kR}$). Observables like the $\ell^+\ell^-$ or $\gamma\gamma$ invariant mass spectra can probe the interaction scale of KK gravitons with matter concluding $kR \gtrsim 11$.

In addition to the graviton one can also allow SM fields to propagate in the factorized EDs. E.g., TeV-scale string compactification [17] with compactification radius $R \gtrsim (7 \text{ TeV})^{-1}$ (from LEP 2) implies gauge fields propagate in the bulk. Gauge-Higgs Unification [18] protects the EW scale by defining the Higgs as a higher-dimensional gauge field component. Universal Extra Dimensions (UEDs) [19] allow all SM particles in the bulk. Grand Unified Theories (GUTs) in EDs with $R^{-1} \approx M_U$ (the gauge coupling unification scale) can solve many problems of conventional supersymmetric GUTs [20]. There are also models with SM fields propagating in warped EDs (but not the Higgs in order to protect the exponential suppression of the EW scale). These can be viewed as dual descriptions of walking TC by virtue of the AdS correspondence with conformal field theories [21]. No fully realistic models exist, but it is interesting that EWS breaking by boundary conditions of gauge fields in warped EDs yield higgsless models [22].
In a QFT, an $h = \pm 3/2$ particle can produce a $1/r^2$-force only if it is coupled supersymmetrically. Conversely, supersymmetry [23] is the only possibility to extend the Poincaré algebra non-trivially and its non-renormalization theorems offer the most elegant solution to the hierarchy problem. Moreover, in models of supersymmetric unification a large $m_t$ correctly predict EWS breaking (a fact that was known [24, 25] even before $m_t$ was measured) and these are further supported by the approximate unification of gauge couplings at $M_U \sim 10^{-16}$ GeV $\lesssim \kappa_4$ in the minimal supersymmetric standard model (MSSM). Finally, the MSSM predicts $M_{h^0} \lesssim 135$ GeV for the lighter of the two CP-even Higgses, in remarkable agreement with Figure 3 (identifying $h^0$ with $H$). The additional assumption of $R$-parity conservation (sufficient to forbid proton decay by dimension 4 operators) implies that the lightest supersymmetric particle is stable offering an explanation for the observed dark matter (a similar statement applies to UED models).

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