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Beyond the Standard Model at the Tevatron and the LHC

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This contribution contains a brief review of several scenarios for physics beyond the Standard Model at the energy scales accessible to experiments at the Tevatron and the LHC, focusing on their experimental signatures.

I. INTRODUCTION

Particle physics at the high-energy frontier is currently being explored by experiments at the Tevatron collider at FNAL. The Large Hadron Collider (LHC) will soon expand the energy frontier, providing proton-proton collisions at a center of mass energy of 14 TeV, a factor of 7 higher than the Tevatron. There are strong theoretical reasons to expect that these experiments will discover physics beyond the Standard Model (SM). However, there is no unique prediction for what form this new physics might take: in fact, over the years, many alternatives have been suggested. In this contribution, I will briefly review several theoretically attractive possibilities, focusing on their experimental signatures at hadron colliders.

Two independent arguments point to the presence of new physics at the TeV scale. First, the SM describes electroweak symmetry breaking (EWSB) in terms of the Higgs mechanism. The mass parameter of the Higgs field receives quadratically divergent one-loop corrections:

\[ \mu^2(M_{ew}) = \mu^2(\Lambda) + c \frac{\Lambda^2}{16\pi^2} + \ldots \]  

where \( M_{ew} \sim 100 \text{ GeV} \) is the EWSB scale, \( c \) is a numerical coefficient of order one, and \( \Lambda \) is the scale at which the quadratic divergence is cut off. This cutoff can be due to either new particles entering the loops, or to strong-coupling phenomena; in either case, physics beyond the Standard Model (BSM) has to enter at \( \Lambda \). Consistent EWSB demands \( \mu^2(M_{ew}) \sim M_{ew}^2 \). This can occur naturally if

\[ \Lambda \lesssim 4\pi M_{ew} \sim 1 \text{ TeV}. \]  

Otherwise, finely tuned cancellation between the two terms on the right-hand side of Eq. (1) is required. Thus, in the absence of fine-tuning, new physics should appear around, or below, the 1 TeV scale.

The second argument has to do with dark matter. While microscopic nature of dark matter is currently unknown, it cannot consist of SM particles. If one postulates a new stable “dark matter particle” \( \chi \), and assumes that this particle is a thermal relic, the measured dark matter density fixes the cross section of the \( 2 \leftrightarrow 2 \) scattering between \( \chi \) and SM states at low \( \chi \) velocities. This cross section is about 1 pb (see Fig. 1), a value typical of a weak-interaction process. This coincidence motivates the hypothesis that the dark matter particle is part of the new physics at the electroweak scale, and indeed many BSM models contain dark matter candidates.

II. SUPERSYMMETRY

Supersymmetry (SUSY) has long been considered a leading candidate for the BSM physics. In SUSY, superpartners of the SM particles appear at the TeV scale. Loops containing superpartners combine with the SM loops to cancel the quadratic divergence in the Higgs mass. The minimal realization of SUSY at the TeV scale, the minimal supersymmetric standard model (MSSM), provides the framework for phenomenological studies. Excellent pedagogical reviews of the MSSM are available \[2, 3\]. Extensive searches for SUSY using electron-positron collisions, heavy
FIG. 1: Total annihilation cross section $\chi\chi \rightarrow $SM, at low $\chi$ velocities, consistent at 2-$\sigma$ level with the WMAP measurement of the dark matter density. For the precise definition of $\sigma_{an}$ and the details of the analysis, see Ref. [1].

flavor probes, and high-precision low-energy measurements, have been performed; for an update, see A. Freitas’s contribution in these proceedings [4].

For a typical point in the MSSM parameter space, superpartner production at a hadron collider is dominated by the strongly-interacting states, the gluino and the squarks. In most cases, these particles decay promptly. If R-parity is conserved, the decays must include the lightest supersymmetric particle (LSP), which is stable. A commonly considered scenario is a weakly interacting LSP (e.g. a neutralino), which could provide a dark matter candidate. In this scenario, every squark/gluino production event at a hadron collider contains missing transverse energy (MET), in addition to jets and possibly leptons from cascade decays. The large MET provides a generic signature for SUSY. The Tevatron collaborations have performed searches for SUSY in the jets+MET channel (see T. Adams’s contribution [5] for an update), and searches at the LHC are planned (see O. Brandt’s contribution [6] for details).

While production cross sections for weakly interacting superpartners at hadron colliders are suppressed, such processes may still offer interesting signatures, e.g. due to distinctive final states. A well-known example is the trilepton signal from chargino-neutralino associated production, which has extremely low SM backgrounds [5].

It is important to keep in mind that the “canonical” SUSY scenario of conserved R-parity with prompt decays to a weakly interacting LSP is only one theoretical possibility within the MSSM. For example, in models with gauge mediation of SUSY breaking, the LSP is typically a gravitino $\tilde{G}$. In this case, the next-to-lightest superparticle (NLSP) can only decay gravitationally, and may be long-lived on the time scale of the detector. The NLSP may be electrically charged, leaving a track in the muon system. (While stable electrically charged particles are in conflict with cosmology, lifetimes up to 1 sec are allowed.) It may be electrically neutral, potentially decaying in the detector into a photon and a gravitino. It is even possible that the long-lived NLSP is strongly interacting, forming exotic color-neutral “R-hadrons” by capturing light quarks. All these possibilities require search strategies different from the canonical scenario. Such searches are being pursued at the Tevatron [5] and will be continued at the LHC [6].

The MSSM has a very large number of free parameters, and experiments typically use more constrained frameworks, such as the CMSSM (a.k.a. mSUGRA), to interpret the data and present the results. However, many models of supersymmetry breaking have been constructed, many predicting superpartner spectra quite different from mSUGRA. Even for a generic signature such as jets+MET, a search formulated within mSUGRA can miss a SUSY signal if the superpartner spectrum does not fit the mSUGRA assumptions. For example, Alwall et. al. [7] show that modifying the mSUGRA-motivated $H_T$ and $\not{E}_T$ cuts in the DØ search in the jets+MET channels can allow the experiment to
In this scenario, SM matter fields must propagate on a 3+1 dimensional submanifold, or “brane”, inside the full space. The experimental signatures of this scenario are of two classes, as outlined below.

![Graph](image)

**FIG. 2**: The 95% c.l. exclusion curve for DØ at 4 fb⁻¹. The dashed line corresponds to the exclusion region using DØ non-optimized cuts. The dotted line shows the gluino and bino masses allowed in mSUGRA. For more details, see Ref. [2].

cover regions in the MSSM parameter space not covered by the present search, see Fig. 2.

In the MSSM, the tree-level mass of the lightest CP-even Higgs boson is predicted to be below $M_Z$. A large loop correction, predominantly from top/stop loops, is required to raise this mass above the lower bound from the LEP 2 direct search, about 114 GeV. There is a certain amount of tension between this requirement and naturalness of the EWSB [3]. Within the MSSM, this tension can be minimized if the stop sector parameters are in the “golden region” [3], where the lighter stop is at 200-300 GeV, there is a few hundred GeV splitting between the two stops, and the rotation angle between the gauge and mass stop eigenstates is large. This hypothesis can be tested by searching for the $t\bar{t}_Z$ decay at the LHC [9, 10]. An alternative possibility is that the Higgs sector is more complicated than that of the MSSM, involving for example additional SM-singlet fields. This may have interesting consequences for Higgs searches (see e.g. S. Chang’s talk at this conference).

### III. EXTRADIMENSIONS

Many models of new physics at the TeV scale involve extra compact dimensions of space. The two large classes of models are those with 2 or more dimensions compactified on a torus, and those with a single “warped” (non-factorizable) extra dimension.

#### A. Flat Extra Dimensions

Arkani-Hamed, Dimopoulos and Dvali suggested that the quadratic divergences in the Higgs mass can be cut off by the physics of quantum gravity (e.g. stringy effects), provided that the fundamental scale of quantum gravity $M_*$ is about 1 TeV [11, 12, 13]. This possibility is consistent with the observed value of $M_{Pl} \sim 10^{19}$ GeV, provided that there are extra dimensions of space with compactification radii $R \gg M_*^{-1}$. For $n$ toroidal extra dimensions with equal radii, the required value is

$$R = M_*^{-1} \left( \frac{M_{Pl}}{M_*} \right)^{2/n}.$$  \hspace{1cm} \text{(3)}

In this scenario, SM matter fields must propagate on a 3+1 dimensional submanifold, or “brane”, inside the full space. The experimental signatures of this scenario are of two classes, as outlined below.
First, there are signatures that can be observed at energy scales below $M_*$, and do not depend (or depend only weakly) on the nature of the quantum gravity theory at $M_*$. One example is radiation of gravitons into extra dimensions in SM collisions, leading to events with a single jet (or photon) and MET in hadronic collisions. Searches for such events are in progress at the Tevatron, as reviewed by Yu [14] in these proceedings, and will be performed at the LHC. Non-resonant anomalies in dilepton, diphoton, and dijet production due to $s$-channel graviton exchanges provide another signature. For example, a DØ search in the dimuon channel puts a bound on the fundamental scale of about 1 TeV [15]. (Note however that comparison between limits from virtual and direct graviton production is difficult, since theory predictions for virtual graviton processes contain unknown order-one coefficients whose precise value depends on the details of quantum gravity theory at $M_*$.)

The second class is the signatures arising from collisions with parton center-of-mass energies of order $M_*$ or above, which directly probe the nature of quantum gravity. At $\sqrt{s} \gg M_*$, parton collisions are expected to produce classical black holes. This possibility received much attention in the literature (see e.g. D. Bourilkov’s contribution [16]). Given the existing constraints on $M_*$ and large theoretical uncertainties [17], it seems rather unlikely that black hole production will occur at the LHC. However, the LHC may be able to explore the more theoretically interesting regime $\sqrt{s} \sim M_*$, where the nature of the microscopic theory of quantum gravity can be gleaned. For example, if weakly-coupled string theory is realized, the LHC experiments should be able to observe string Regge excitations of the SM particles, e.g. a massive spin-2 color-octet “Regge gluon” [18, 19]. A realistic detector-level studies of the LHC sensitivity to such Reggeons would be welcome.

### B. Warped Extra Dimensions

Randall and Sundrum (RS) suggested an alternative model with a single extra dimension, with a non-trivial metric [20]:

$$ds^2 = e^{-2k|y|}dx_0^2 + dy^2$$

(4)

where $k$ is the curvature. The extra dimension is compactified on an $S/Z_2$ orbifold, such that $y \in [0, r_c]$. In the original version of the model, the SM fields were assumed to be localized on a four-dimensional brane located at $y = r_c$. The quadratic divergence in the Higgs mass is cut off at the effective Planck scale on that brane, which is given by $M_{\text{eff}} = M_* e^{-kr_c}$, while the 4D Planck scale is close to $M_*$. A large hierarchy $M_{\text{eff}} \ll M_*$ can be generated with a modest value of $kr_c$: choosing $M_{\text{eff}} \sim 1$ TeV requires $kr_c \sim 30$. In this version of the model, the experimental signatures arise from the couplings of Kaluza-Klein (KK) excitations of the graviton to the SM states. The KK gravitons can appear as resonances in dilepton, diphoton or dijet channels. Tevatron searches for such resonances place interesting bounds on the model: for example, for $k/M_* = 0.1$, the lightest KK graviton mass below 900 GeV is currently ruled out [21, 22].

Over the last few years, much theoretical attention was attracted by versions of the RS model in which all SM fermions and gauge bosons are assumed to be propagate in the bulk of the 5D space. This framework can provide a natural explanation of the mass hierarchy among the quarks and leptons of the SM [23, 24], natural suppression of flavor-changing effects and corrections to precision electroweak observables [25, 26, 27, 28, 29], and the possibility of gauge coupling unification with precision similar to the MSSM [30]. It also opens up an interesting possibility of consistent gauge-Higgs unification [31, 32, 33]. In this framework, all SM fermions and gauge bosons have KK modes, leading to a potentially rich phenomenology at the TeV scale. However, the wavefunctions of the KK modes are localised near the TeV boundary ($y = r_c$), whereas the wavefunctions of light SM quarks and leptons are localized near the Planck boundary ($y = 0$). (The SM gauge bosons have flat wavefunctions.) This effect suppresses the production of the KK modes at the LHC. The KK gluon has the largest cross section, and is probably the most realistic target at the LHC in these models [34, 35]. However, the KK gluon decays primarily into top pairs (see Fig. 3). In the KK gluon mass range allowed by precision electroweak constraints (about 3 TeV and above), the tops from the KK gluon decay are moving relativistically. The highly boosed tops present an experimental challenge, since their decay products are typically collimated into a single “top jet”. Identification of such top jets is an active
area of current research [36, 37, 38]. Another interesting prediction of this model is a large enhancement of the $t \to cZ$ branching ratio, due to the composite nature of the right-handed top. This decay should be observable at the LHC [39].

An interesting variation of this construction is the Higgsless model [40]. In this model, there is no Higgs boson. Instead, electroweak symmetry breaking is achieved by imposing boundary conditions on the 5D gauge fields whose lightest KK modes correspond to the W and Z bosons. This model can be thought of as a five-dimensional “dual” (in the spirit of the AdS/CFT correspondence) of the familiar 4D technicolor models. The 5D version of the model allows for improved calculability. In this version, fermion masses can be straightforwardly incorporated [41], and precision electroweak constraints can be satisfied. In particular, a custodial SU(2) symmetry can be incorporated to forbid tree-level contributions to the $T$ parameter, while the $S$ parameter can be suppressed by a special choice of the fermion wavefunctions in the fifth dimension [42]. This choice also suppresses the couplings of the electroweak gauge boson KK excitations to light fermions. An interesting phenomenological prediction of the model is the presence of light (below 1 TeV), narrow resonances in vector boson scattering channels, which can be explored at the LHC. The charged resonance $V^\pm$ appearing in the $WZ$ channel is especially interesting, since there is no resonance in this channel in the SM with a Higgs or the MSSM. The coupling of this resonance is fixed by the unitarity sum rules [43, 44], and its production cross section can be predicted unambiguously, see Fig. 4. Using the golden three-lepton channel, the $V^\pm$ should be discovered with about 100 fb$^{-1}$ of data at the LHC if the model is correct [44, 45]. Purely four-dimensional
versions of the Higgsless model, e.g. a “three site model” \[46\], can be obtained via dimensional deconstruction, and proved useful in phenomenological analyses.

IV. LITTLE HIGGS MODELS

In analogy with pions, one can attempt to explain the lightness of the Higgs by interpreting it as a *Nambu-Goldstone boson* (NGB) corresponding to a spontaneously broken global symmetry of an extended electroweak sector. However, gauge and Yukawa couplings of the Higgs, as well as its self-coupling, must violate the global symmetry explicitly, since an exact NGB only has derivative interactions. Quantum effects involving the symmetry-breaking interactions generate a potential, including a mass term, for the Higgs. Generically, this radiative mass term is of the same size as in a model where no global symmetry exists to protect it: that is, the NGB nature of the Higgs is completely obliterated by quantum effects. A solution to this difficulty has been proposed by Arkani-Hamed, Cohen and Georgi \[47\]. They argued that the gauge and Yukawa interactions of the Higgs can be incorporated in such a way that a quadratically divergent contribution to the Higgs mass is *not* generated at the one-loop order. The cancellation of this contribution occurs as a consequence of the special “collective” pattern in which the gauge and Yukawa couplings break the global symmetries. In diagrammatic terms, the SM one-loop corrections are cancelled by the loops of exotic TeV-scale states of the same spin: for example, loops involving the heavy Dirac fermion $T$ cancel the top loop, as shown in Fig. 5.

The remaining quantum contributions (e.g. from two-loop diagrams) are sufficiently small so that the theory may be valid up to an energy scale of order 10 TeV without fine-tuning. “Little Higgs” (LH) models implement this idea to obtain natural and realistic theories of EWSB with a light Higgs boson. They predict new particles and interactions at the TeV scale. Above 10 TeV, the LH models break down and need to be extended, or “UV-completed”. However, the precise nature of UV completion is unimportant for the discussion of the searches for LH at the Tevatron and the LHC.

Many LH models have appeared in the literature. (For reviews and references, see \[48, 49\].) In particular, the “Littlest Higgs” model \[50\] was the focus of the initial studies of the LH collider phenomenology \[51, 52\]. Unfortunately, early LH modes, including the Littlest Higgs, suffered from severe constraints from precision electroweak fits. These constraints are elegantly avoided by the introduction of T Parity \[53\], a discrete $Z_2$ symmetry under which all the Standard Model (SM) states are even, while most new states of the LH model are odd. The T-parity is analogous to the familiar R-parity of the MSSM, and has similar phenomenological consequences: in particular, the lightest T-odd particle (LTP) is stable. Many LH models can be extended to incorporate T Parity. The Littlest Higgs model with T Parity (LHT) \[54\] is a simple and realistic example, and became the benchmark model for phenomenological studies. Precision electroweak constraints on the LHT have been analyzed at the one-loop level \[55\], and shown to be consistent with natural EWSB. A variety of constraints from flavor-changing neutral currents have been considered (see for example \[56\]), and can be easily satisfied. The model also provides an attractive dark matter candidate \[57, 58\], since the LTP is typically a weakly-interacting partner of the SM hypercharge gauge boson $B'$.

The LHT model contains a heavy T-odd Dirac fermion partner for every *left-handed* SM fermion. The T-odd quarks $Q'$ dominate the production at hadron colliders in most of the parameter space. (Note that the minimal version of the LHT does not contain a T-odd partner of the gluon, although such particle may be easily incorporated...
if demanded by data.) Once produced, the T-odd quarks decay promptly. The decay $Q' \rightarrow qB'$ is open throughout the parameter space; depending on the parameters, other more complicated decay chains may be available as well. Since the LTP is weakly-interacting, this process will lead to a jets+MET signature in the detector. The existing DØ searches for jets+MET in the contexts of SUSY and leptoquarks can be used to place exclusion bounds on the parameters of the LHT model \[59\]. For large mass splitting between the T-odd quarks and LTP, the Tevatron should be able to exclude T-odd quarks as heavy as 400 GeV with 8 fb$^{-1}$ of data, see Fig. 6. The LHC can cover most of the interesting parameter range. Signals with MET associated with leptons may also be available at the LHC \[57, 60, 61\].

Another interesting feature of the LHT model is the presence of a T-even partner of the SM top. Searches for such a particle discussed in the context of the Littlest Higgs without T-parity \[52, 62, 63\] remain applicable, although the branching ratios may be modified due to the possibility of decays into T-odd top states.

Recently, it was pointed out that the LH models may contain T-parity violating operators induced by anomalies, similar to the Wess-Zumino-Witten operator in the chiral lagrangian for pions \[64\]. Such operators do not contribute significantly to precision electroweak observables, so the model can still be viable, even though T-parity is broken. However, they can dramatically affect collider phenomenology: for example, the LTP decays to two weak gauge bosons can be induced, resulting in spectacular events at the LHC \[65, 66\]. In addition, since the LTP is unstable, there is no dark matter candidate. Whether or not the T-violating operators are actually present depends on the structure of the UV completion of the LH model: for example, explicit UV completions have been recently constructed in which T-parity remains an exact symmetry at the quantum level \[67, 68\].

V. OUTLOOK

The naturalness of EWSB and the potential connection of the observed dark matter density to electroweak physics provide compelling reasons to expect new phenomena at the TeV scale. Many theoretical ideas about the nature of these new phenomena have been explored in the last three decades, resulting in a huge "landscape" of possibilities. A few popular ideas have been briefly reviewed in this talk; large parts of the landscape, however, could not be discussed due to time constraints. In particular, I have focused on models directly motivated by the hierarchy problem. Another interesting direction is to consider models that, while not directly addressing this problem, could nevertheless be part of the TeV-scale physics, and lead to interesting new experimental signatures. Recent examples in this class include hidden valleys \[69\], unparticles \[70\], and quirks \[71\].
The Tevatron experiments have been steadily expanding the high-energy frontier, eliminating some of the available model space. In the coming years, experiments at the LHC should provide definitive tests of the scenarios discussed here and other candidate models of the TeV scale physics. It is gratifying that in a few years, the list of viable ideas should be considerably shorter than it is today.

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