PHYSICS BEYOND THE STANDARD MODEL AND ITS MINIMAL SUPERSYMMETRIC EXTENSION AT LARGE COLLIDERS*

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New large colliders will probe scales up to few TeV, indicating the way Nature has chosen to extend the Standard Model. We review alternative scenarios to the traditional Minimal Supersymmetric Standard Model: the little Higgs model, split supersymmetry and extra dimensional models with low energy signals.

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1. Introduction

It is believed that the Standard Model (SM) is an effective low energy theory which has to be completed at some scale to include gravity. What aspects of this extension will show up first at large colliders will have to wait for new experimental data. In order to establish a departure from the SM predictions it will be probably necessary a new large striking signal. However, we will have to start carefully looking at the processes where the SM is less precisely known, like at the top or at the Higgs, or where clean signals can be observed, like lepton pair or monojet production.

The most popular low energy extension of the SM is the Minimal Supersymmetric Standard Model (MSSM). Its main virtues are to make less severe the hierarchy problem: how to keep the Higgs boson mass 16 orders of magnitude lighter than the Planck scale $\sim 2.4 \times 10^{18}\,\mathrm{GeV}$, and to unify the gauge coupling constants of the three SM interactions near this scale.

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Its phenomenology is discussed in other contributions to these proceedings (see [1–5] for some recent reviews where this network has contributed). However, there are also other SM extensions which ameliorate its fine-tuning problems, and whose signatures can be also observable at large hadron colliders, like the Tevatron and the LHC, or at a large (International) Linear lepton Collider (ILC). In the following we review some of the implications of recent alternatives which may manifest at the top (Sec. 2), at the Higgs (Sec. 3), in lepton pair production with a large invariant mass (Sec. 4), and/or as an excess of monojets (Sec. 5).

Two generic examples of alternative scenarios are the Little Higgs Model [6–8] and large Extra Dimensions [9,10] (for recent (phenomelogical) reviews see [11, 12]). The former explores our knowledge of four-dimensional gauge theories. It improves the hierarchy problem related with the stability of the Higgs mass enlarging the SM to include a larger global symmetry at a higher scale $\sim$ TeV, with a locally gauged subgroup containing the SM gauge group. Its breaking above the TeV is communicated to the SM Higgs doublet, which is a pseudo-Goldstone boson, through radiative corrections, and then, it is delayed by factors of 4π times coupling constants. The extra fields of its littlest version [7] are a charged 2/3 vector-like quark T, a complex scalar triplet ϕ, and four new gauge bosons $A_H, W_H^{\pm}, Z_H$; all of them with masses near the TeV scale, and eventually observable.

On the other hand, the possibility of having observable large Extra spatial Dimensions raised in [9,10] allows to reformulate the hierarchy problem. In this scenario there is only one fundamental scale of the order of the TeV, with some models being even Higgsless [13]. The SM fields must mainly live in our four-dimensional brane, but can propagate, as does gravity, in the Extra Dimensions depending on the model assumptions. In this case new physics manifests as towers of Kaluza–Klein (KK) states, which, if light enough, would be observable at large colliders. Thus, we may want to know how to search for them. In practice, one can consider only the first massive states as we do below: new gauge bosons with the SM couplings but with heavier masses, new vector-like fermions with the SM quantum numbers and/or extra scalar replicas.

This new framework also offers a new playground for dealing with other SM puzzles, as for instance, the necessity of accommodating the very different fermion masses observed in Nature. The paradigmatic example is the very small neutrino masses. It was pointed out in [14] that if Right-Handed (RH) neutrinos living in the bulk exist, their wave-function values on the brane where the standard Left-Handed (LH) neutrinos stay can be effectively so small as to explain the tiny Dirac neutrino masses observed; although to write definite realistic models, other mechanisms may be also required. The neutrino mass generation (see [15] for a review, and [11] for

the Extra Dimensional view), as the measured neutrino masses m_ν, is not directly distinguishable at large colliders, because any related effect is suppressed by very small ratios $\sim (m_\nu/\sqrt{s})$, where $\sqrt{s}$ is the collider center of mass energy. New neutrino effects at colliders must be associated to leptons with masses $\sim \sqrt{s}$ and relatively large mixings with the SM fermions. These new leptons (neutrinos), which may be also light KK modes, are discussed in other contribution to these proceedings [16] (see also [17–19] and references therein).

Here we will be concerned with the (top) quark sector. The observed hierarchy between the light quarks and the top can be related to their localisation in the Extra Dimensions [20]. Indeed, simple models with one extra dimension and quarks propagating in the bulk can reproduce the observed pattern of quark masses and mixings [21], and predict new vector-like quarks below the TeV scale. Hence, a precise measurement of the top coupling V_{tb} and the search of new heavy quarks at large colliders will constrain these models as well.

Both SM alternatives, the Little Higgs Model and the large Extra Dimensions, are more a class of models than definite complete theories. Their predictions are mainly estimates which may depend on unexpected new effects. This is the case in models with Extra Dimensions, for instance, of the so-called Brane Kinetic Terms (BKT). These are corrections to the kinetic terms of the bulk fields which are localised at the branes. They were first discussed in the context of gravity [22], but they are generated for bulk fields already at one loop in compactification with defects, as for instance in orbifolds [23]. They are phenomenologically relevant [24–26], and deserve further theoretical study [27] (see [28] for a more complete set of references). A review [29] can be found in these proceedings.

Finally, as a last recent example of alternative to the MSSM it is worth to mention Split Supersymmetry [30,31]. In this proposal squarks and sleptons are very heavy and can not even mediate the dominant decays of gauginos and higgsinos, which remain near the electroweak scale. The SM superpartners are thus split. The plethora of new sparticles expected to be produced at forthcoming experiments in the MSSM gets reduced to some new (Majorana) fermions appearing, as we shall comment in Sec. 5, mainly as missing energy, plus a jet, for instance, in the gluino case. A general discussion of the main phenomenological differences with traditional low-scale supersymmetry (SUSY), with emphasis in the cosmological aspects, is given in [32].

2. Signals at the top

Large colliders will be top factories. In particular the LHC with a cross section of 860 pb will produce tens of millions of top pairs [33] (see also [34,35] in these proceedings), and a large number of pairs of any new heavy quark

which may exist with a mass up to several TeV. Single top production will be down by more than an order of magnitude, but it will give the best measurement of the top coupling to the W, V_{tb}, with an expected precision of 5% [36]. The top coupling to the Z, X_{tt}, will be measured with a better precision at ILC, 2% [3]. These two measurements could give evidence of new physics if different from their SM values $V_{tb}^{\rm SM} = 0.999$ and $X_{tt}^{\rm SM} = 1$, respectively. The most probable explanation of such a large deviation $V_{tb} < 0.96$ from the SM predictions would be the top mixing with other vector-like quark of charge $2/3$, T [37]. As emphasized in the Introduction, alternative SM extensions like the Little Higgs Model or Extra Dimensions predict such new vector-like quarks [7, 21].

In the simplest case of only one effective light T quark the $t - T$ quark system is parameterised by the two quark masses $m_t < m_T$ and its mixing angle

$$V_{Tb} = \sqrt{1 - V_{tb}^2}\,. \tag{1}$$

($V_{tb}^{\rm SM}$ can be taken equal to 1). The corresponding mass matrix reads

$$\begin{pmatrix} m_t & V_{Tb} m_T \\ 0 & m_T \end{pmatrix}, \tag{2}$$

where the RH quarks (columns) have been rotated and the field phases chosen conveniently, and $V_{Tb} \sim \mathcal{O}(0.1) \ll 1$ is a small expansion parameter. The physics of this SM addition has been often discussed in the literature [38]. We follow the analysis in [39]. The main constraint from precise electroweak data results from the *oblique* parameter [40]

$$\boldsymbol{T} = 0.12 \pm 0.10\,. \tag{3}$$

This latest value differs significatively from the value quoted in [41] but it has been obtained fixing the parameter $\boldsymbol{U} = 0$, what seems more adequate for this type of SM extensions. $\boldsymbol{T}$ is a function of the T mass and of its couplings to the W and to the Z squared, $|V_{Tb}|^2$ and

$$|X_{Tt}|^2 = |V_{Tb} V_{tb}|^2 = |V_{Tb}|^2 (1 - |V_{Tb}|^2)\,, \tag{4}$$

respectively. Its approximate expression can be written ($m_t^2 \ll m_T^2$)

$$T = \frac{N_c}{16\pi \sin^2\theta_W \cos^2\theta_W} |V_{Tb}|^2 \left[-18.4 + 7.8 \log \frac{m_T^2}{M_Z^2} + O\left(\frac{M_Z^2}{m_T^2}\right) \right], \tag{5}$$

where $N_c = 3$ is the number of colours, and $\sin^2\theta_W = 0.231$ and m_t taken equal to 176 GeV are the $\overline{\rm MS}$ values of the electroweak mixing angle and the

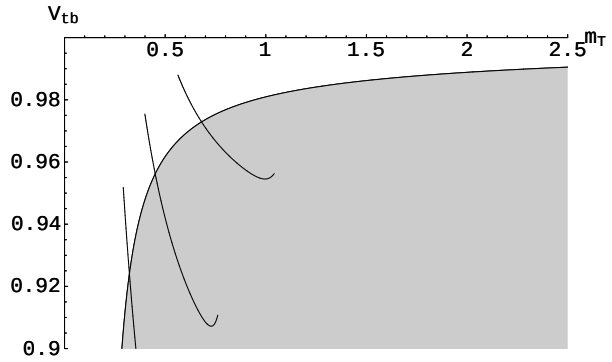


Fig. 1. Excluded region (shadowed) in the m_T–V_{tb} plane defined by requiring the $\boldsymbol{T}$ parameter to deviate by more than $3\,\sigma$ from its experimental value. Lines show the m_T–V_{tb} values for models with an extra dimension parameterising the orbifold $\frac{S^1}{Z_2}$ and radius $R = \frac{1}{M_c}$ with $M_c = 0.5,\ 0.7,\ 1\,\mathrm{TeV}$, from left to right. The points along the lines correspond to growing BKT coefficients, from 0 to $20\,R$ from right to left.

top mass at the $M_Z = 91.2\,\mathrm{GeV}$ scale, respectively. In Fig. 1 we plot the experimentally excluded region (shadowed) of the m_T–V_{tb} plane [26]. The limiting curve defines the 3 standard deviation bound $\boldsymbol{T} \leq 0.29$, and only masses and mixings on the top-left part are allowed.

In the Little Higgs Model [8]

$$V_{Tb} = \frac{\lambda_1}{\lambda_2}\frac{m_t}{m_T} \qquad \text{and} \qquad V_{tb} = 1 - \frac{1}{2}\frac{\lambda_1^2}{\lambda_2^2}\frac{m_t^2}{m_T^2}\,, \tag{6}$$

with $\lambda_{1,2}$ two couplings of $\mathcal{O}(1)$ satisfying

$$\frac{1}{\lambda_1^2} + \frac{1}{\lambda_2^2} \simeq \frac{v^2}{m_t^2}\,, \tag{7}$$

where $v = 246\,\mathrm{GeV}$ is the Higgs doublet vacuum expectation value, and m_T naturally ranging from 1 up to 5 TeV, but otherwise arbitrary. (In more restrictive models of this class the non-observation of an excess of lepton pairs at Tevatron banishes m_T to higher values [42].) Then Eq. (5) and the $3\,\sigma$ limit on $\boldsymbol{T}$ above further constrain

$$\frac{\lambda_1}{\lambda_2} \leq \frac{m_T(\mathrm{TeV})}{\sqrt{0.681 + 0.560\log m_T(\mathrm{TeV})}}\,, \tag{8}$$

for large m_T. Hence, already for $m_T = 1\,\mathrm{TeV}$, $V_{tb} > 0.96$, and no distinction between the Little Higgs Model and the SM can be made with the foreseen precision for the V_{tb} measurement. On the other hand, models with Extra

Dimensions and multilocalisation can accommodate smaller m_T and V_{tb} values [21]. In these models they fix two free parameters: the five-dimensional top mass and the position of the intermediate brane. The allowed $m_T - V_{tb}$ region can be also reached in the simplest models without multilocalisation if relatively large BKT are included [26]. In Fig. 1 we draw lines of constant compactification scale M_c and growing BKT from right to left. A model with excluded values in the shadowed region can predict allowed m_T masses and V_{tb} couplings increasing (moving from right to left along the lines) the BKT coefficient. In summary, a new vector-like T quark with a large mixing with the top could be the first signal of Extra Dimensions.

Even if the mixing of such a new quark is too small to be observed, it could still be produced at LHC if its mass is up to few TeV. In Fig. 2 we plot the cross sections for different T production processes at LHC [5, 8].

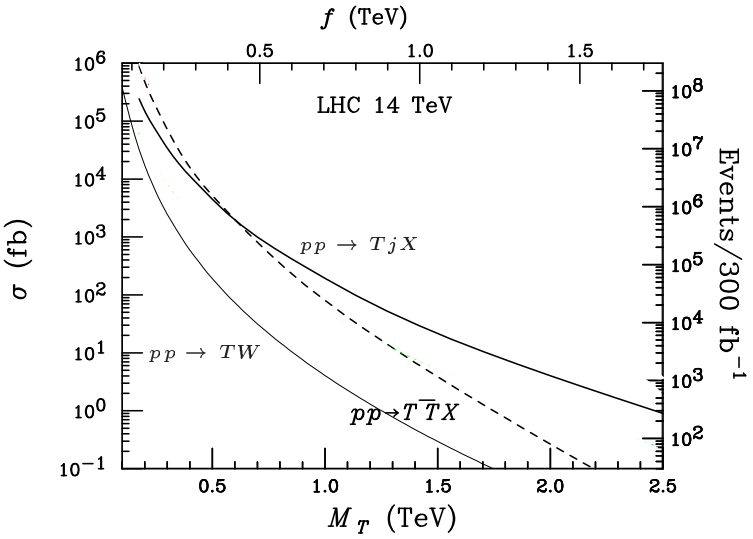


Fig. 2. Cross sections for different T production processes at LHC: $pp \to T\bar{T}X$ (dashed), $pp \to TjX$ (thick solid) and $pp \to TWX$ (thin solid).

$T\bar{T}$ production is fixed by QCD and its cross section decreases faster with m_T because the t-channel interchanges the T quark and the s-channel is relatively suppressed at high energy (Fig. 3(a)). Tj production is model dependent. In Fig. 3(b) we show the dominant process. The cross section in Fig. 2 corresponds to $V_{Tb} = \frac{m_t}{m_T}$. In the Little Higgs Model a ratio $\frac{\lambda_1}{\lambda_2} = \frac{1}{2}$ in Eq. (6) would stand for a factor 4 smaller cross section. Larger ratios are constrained by Eq. (8). The upper variable f in this figure is the parameter fixing the scale of new physics. The plotted values correspond to the lower limit $f \lesssim \frac{v}{2m_t} m_T$. Models with Extra Dimensions can show a similar V_{Tb}

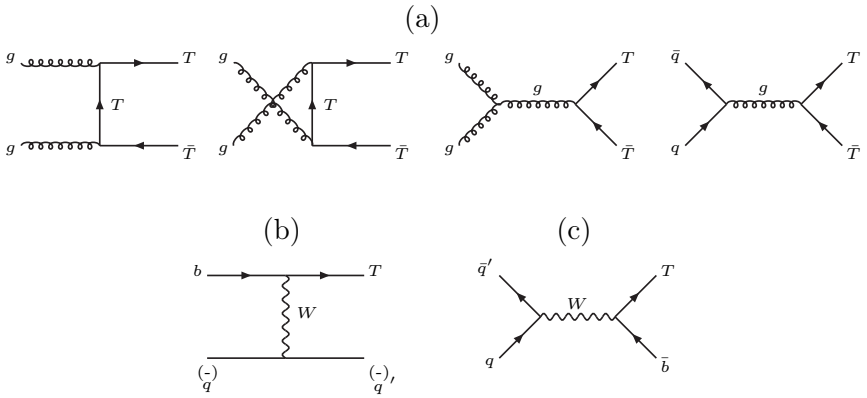


Fig. 3. (a): Diagrams for $T\bar{T}$ production. (b) and (c): t- and s-channel contributions, respectively, to Tj production.

dependence [21]. The s-channel (Fig. 3(c)) is very much suppressed, because although it involves the same vertices as the t-channel, it has the high energy s-channel suppression relative to t-channel contribution. We also plot in Fig. 2 the TW cross section. The corresponding diagrams are depicted in Fig. 4. Although there is the enhancement of a strong coupling vertex

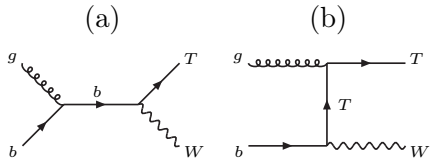


Fig. 4. s-channel (a) and t-channel (b) TW production diagrams.

and an initial gluon relative to the Tj contributions, the exchange of a T quark in the t-channel diagram (Fig. 4(b)) and the s-channel suppression at high energy (Fig. 4(a)) reduce this cross section below the other processes. However, to decide about the best signal one also must wonder about the background. In Table I we give an estimate for the three cases. Jets are required to have a transverse momentum $p_{\mathrm{t}}^{j} > 40\,\mathrm{GeV}$, a pseudorapidity $|\eta_j| < 2.5$ and a separation $\Delta r(jj) > 0.7$. In all cases we assume that T decays into Zt, what typically does 1/4 of the time [8, 44], for it gives the cleanest signal. The largest T cross section, Tj production, has also the largest background, but it can be reduced by a large factor, as also can the

TABLE I

SM background estimates for different T production processes evaluated with ALPGEN [43].

T production process	$pp \to T\bar{T}X$	$pp \to TjX$	$pp \to TWX$
SM background	$pp \to ZZWWjjX$	$pp \to ZWjjX$	$pp \to ZWWjX$
Estimate	4×10^{-4} pb	6 pb	8×10^{-2} pb

other backgrounds, requiring the $t \to Wb$ and the $T \to Zt$ reconstruction (cutting in the corresponding invariant mass distributions). Cross sections must be multiplied in all cases by the corresponding branching ratios when looking at specific channels.

3. A non-standard Higgs

The SM Higgs physics as well as the SUSY and the Two-Higgs Doublet Model (2HDM) [45] (see also [46]) Higgs sector are reviewed in other contributions to these proceedings [47,48]. Here we concentrate on the types of models discussed in the Introduction.

The complete reconstruction of the Higgs potential necessarily requires the measurement of the Higgs self-couplings. These include a trilinear and a quartic interaction, parameterised by the coupling constants λ_{HHH} and λ_{HHHH}, which in the SM take the values

$$\lambda^{(0)}_{HHH} = -\,3\,\frac{M_H^2}{v}\,, \quad \lambda^{(0)}_{HHHH} = -\,3\,\frac{M_H^2}{v^2}\,, \tag{9}$$

where M_H is the Higgs mass. A direct measurement of λ_{HHH} can be obtained, both at LHC and ILC, via the detection of Higgs boson pairs, while, due to the vanishingly small 3-Higgs production cross section, there is no hope for a measure of λ_{HHHH}. Several models predict sizeable departures of λ_{HHH} from its SM value. For example, a scan over the parameter space of the 2HDM shows that values of $r \equiv \lambda_{HHH}/\lambda^{(0)}_{HHH}$ such as $-15 < r < 15$ are quite possible [49].

A second example is the Little Higgs Model [8], with

$$1 \le r \simeq 1 + \delta_r \qquad \text{and} \qquad \delta_r = \frac{\lambda^2_{h\phi h}}{\lambda_{\phi^2}\lambda^{(0)}_{HHH}}\,, \tag{10}$$

where $\lambda_{h\phi h}$ and λ_{ϕ^2} are coefficients of the enlarged Higgs potential after the spontaneous breaking of the assumed global symmetry. Besides the usual

complex scalar doublet h, this Littlest Higgs Model potential contains an additional complex scalar triplet ϕ. Then, the quartic Higgs doublet self-coupling λ_{h^4}, which also gives λ_{HHH}, is not any more only fixed in terms of the Higgs mass and v, but of this ratio of Higgs potential couplings function of the fundamental parameters of the model: gauge and Yukawa couplings, and loop coefficients.

In Fig. 5 we show the effect, at LHC, of varying λ_{HHH} independently of any other SM parameter [49]. Notice that the cross sections do not vanish at zero values of λ_{HHH} because of the presence of diagrams where the two Higgses are radiated independently, with strength proportional to the Yukawa or gauge couplings. The two vertical lines correspond to the limits given in Eq. (10) with $\delta_r = 5.1$. The region at the right of the thin dashed line is accessible for a $3\,\sigma$ discovery at LHC when $M_H \sim 120\,\text{GeV}$. Such a discovery limit has been computed with a detailed signal-to-background analysis performed with `ALPGEN` [43]. This measurement with a large deviation from the SM prediction would further constrain this class of models.

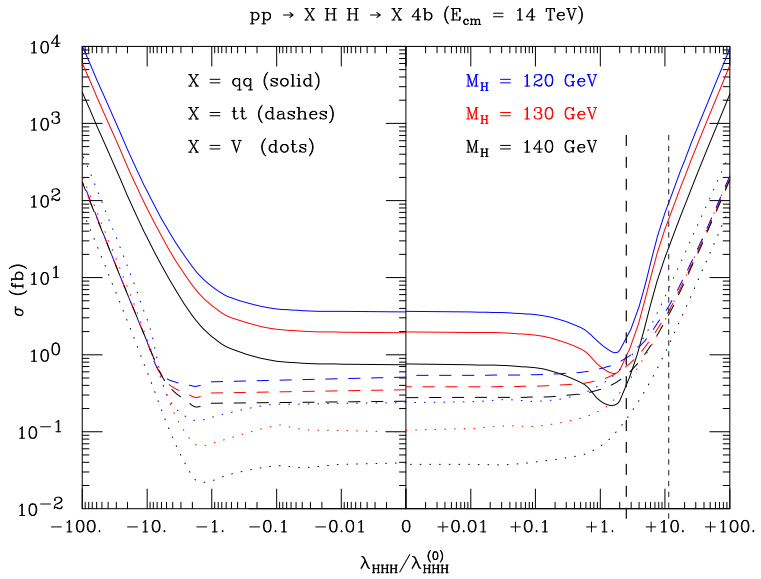


Fig. 5. Dependence of the cross sections for the three processes $qq^{(\prime)} \to qq^{(\prime)}HH$, $gg, q\bar{q} \to t\bar{t}HH$ and $q\bar{q}^{(\prime)} \to VHH$ on $r = \lambda_{HHH}/\lambda^{(0)}_{HHH}$, in correspondence of three values of the Higgs mass.

Finally, the Higgs decay rates also show a dependence on the model, especially the induced decays: $H \to gg, \gamma\gamma$. This variation is expected to be relatively small in the Little Higgs Model, and difficult to observed at LHC or ILC [50].

In models with Extra Dimensions the Higgs can mix with the new singlet scalars associated to the background metric. For instance, this mixing with the radion in the Randall–Sundrum model [10] also modifies the Higgs mass and decay rates. The universal coupling of the metric to the energy-momentum tensor gives no variation in the Higgs branching ratios into massive states but modifies the total and partial decay rates, as well as the induced decay $H \to gg$ branching fraction [51]. These modifications can be larger if the model has a non-minimal Higgs sector, as in the case of the 2HDM [5].

4. Large di-lepton signals

Lepton pair production is expected to be the main production channel to discover and to study new gauge bosons at LHC and ILC (see [52] for a review). An excess of lepton pairs with a large invariant mass can be also the signature of a tower of KK gravitons [12]. As a matter of fact, the large variety of models which predict new contributions to this final state will require a detailed study of this signal, and of other channels, to characterise its origin. A resonant peak periodically repeated will point out to Extra Dimensions, but the mass of the first resonance will constrain the type of model. For instance, if relatively heavy, it will disfavour universal Extra Dimensions [53]. On the other hand, its angular distribution will determine the spin assignment, which can be measured at the LHC, as well as at the ILC [54, 55].

In any case a detailed analysis of this final state together with other related channels, like W pair production or even quark pair production, shall help to distinguish between models, for example, establishing its Higgsless character [56]. (The simplest versions of Higgsless models [13] give a too large $\boldsymbol{S}$ *oblique* parameter [56, 57], but this could be cured [58].)

The Little Higgs Model also predicts new heavy gauge bosons with characteristic decay rates [8]. For a review of the phenomenology of SM gauge extensions, like for instance those based on E_6, see [59] and references there in.

5. Jets beyond the SM

As in the case of di-leptons, missing energy is a signal of many SM extensions, supersymmetric or not. For example, any new neutral gauge boson coupling to quarks and neutrinos, as those predicted by the Little Higgs Model [8], would increase the SM background for mono-jets. In models with Extra Dimensions KK gravitons which escape detection can be also produced with a jet [2].

This signature is also characteristic of SUSY models. The most recent alternative to the MSSM, Split SUSY, can manifest as a mono-jet excess if the gluinos, which are assumed to be relatively light, hadronise little [60]. For a general discussion of the phenomenology of this new scenario see [32].

6. Conclusions

Alternatives to the SM beyond the MSSM like the Little Higgs Model, Models with Extra Dimensions (Higgsless or not) or Split SUSY offer a distinctive solution to the hierarchy problem, and then new physics at the TeV scale which can be eventually observed at large colliders. We have reviewed some of their implications for top and Higgs physics, and in di-lepton and monojet production. These two channels are the signature of many SM extensions and we have essentially referred to the literature. In Table II we gather the signal and collider where to test each class of models. See [5] for a recent review of these alternatives.

TABLE II

Signals of alternative SM extensions at large colliders.

Signal	Collider	New physics
Small V_{tb} (X_{tt})	LHC (ILC)	Extra dimensions
New T quark of charge $\frac{2}{3}$	LHC	Extra dimensions Little Higgs model
Non-standard trilinear Higgs coupling	LHC	Extra dimensions Little Higgs model
Higgs decay rates	LHC/ILC	Extra dimensions Little Higgs model
Large di-lepton production	LHC/ILC	Extra dimensions Little Higgs model
Non-standard jet cross sections	LHC	Extra dimensions Little Higgs model Split SUSY

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