Higgs Boson and New Physics at the LHC

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Abstract. Finding the Standard Model scalar (Higgs) boson is arguably the single most important mission of the LHC. In addition, the LHC hopefully will do its utmost to uncover direct evidence for physics beyond the standard model. In this limited amount of space, in addition to the Higgs boson, I will very briefly discuss low energy supersymmetry and warped extra dimension.

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STANDARD MODEL

The standard model (SM) is a remarkably successful theory for the strong, weak and electromagnetic interactions at present energies. I begin by briefly summarizing its most salient features:

$$\text{Gauge Symmetry} \quad \underbrace{SU(3)}_{\text{QCD}} \times \underbrace{SU(2) \times U(1)}_{\text{EW}}$$

$$\begin{array}{cc} \downarrow & \downarrow \\ \text{confined phase} & \text{partial higgs phase} \\ \text{asymptotic freedom} & \end{array}$$

There are 15 chiral fields per family ($i = 1,\ 2,\ 3$ - color index) , such that the gauge anomalies cancel;

$$\begin{pmatrix} u_i \\ d_i \end{pmatrix},\ u_i^c,\ d_i^c, \begin{pmatrix} \nu_e \\ e \end{pmatrix},\ e^c \tag{1}$$

The electroweak sector is spontaneously broken by the SU(2) Higgs doublet acquiring a non-zero vacuum expectation value:

$$\begin{array}{c} \langle h \rangle \neq 0 \text{ breaks } SU(2) \times U(1) \longrightarrow U(1)_{\text{em}} \\ (cf\!: \ \text{Superconductor } U(1)_{em} \longrightarrow Z_2) \end{array} \tag{2}$$

As a consequence, charged fermions & $W^{\pm}$, Z acquire masses. There are many experimentally verified predictions of the SM :

- Weak Neutral Currents

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- Parity Violation in Atoms
- $W^{\pm}$, Z gauge bosons, Gluon Jets
- Asymptotic Freedom
- c, t, b quarks; CP violation
- Numerous other tests (Stable proton $\tau_p \geq$ few $\times 10^{33}$yrs)
- ? Higgs boson ($m_h \gtrsim 114$ GeV)

The most outstanding still to be verified prediction of the SM has to do with the existence of a neutral Higgs boson whose mass, according to LEP II , is greater than 114 GeV . It is not too much to hope that the Higgs will be the first new particle that will be found at the LHC.

What does the SM have to say about the Higgs boson mass? The mass m_h is given by

$$m_h = \sqrt{\lambda} v, \tag{3}$$

where the quartic coupling λ satisfies the two loop renormalization group equation

$$\frac{d}{dt}\lambda = \frac{\lambda}{16\pi^2}\left[12\lambda^2 - 12h_t^2 + \cdots\right]. \tag{4}$$

From arguments based on vacuum stability and perturbativity, and assuming no new physics between M_Z and M_{Planck}, one obtains the bounds

$$0.8 \lesssim \lambda \lesssim 1.1 \tag{5}$$

which yields the bounds (See Fig. 1)

$$130 \text{ GeV } \lesssim m_h \lesssim 180 \text{ GeV}. \tag{6}$$

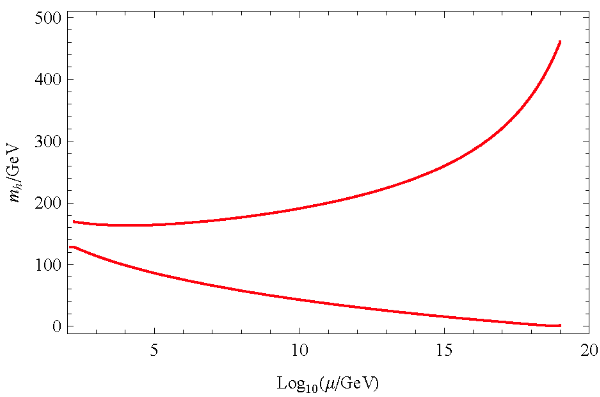

FIGURE 1. SM Higgs bounds

This bound ignores the fact that the observed neutrinos have tiny but non-zero masses, as determined from the atmospheric and solar neutrino experiments. Within the SM framework it is not possible to achieve neutrino masses , from dimension five operators, in excess of 10^{-5} eV or so. This falls well short of 0.05 eV and 0.01 eV (or so)

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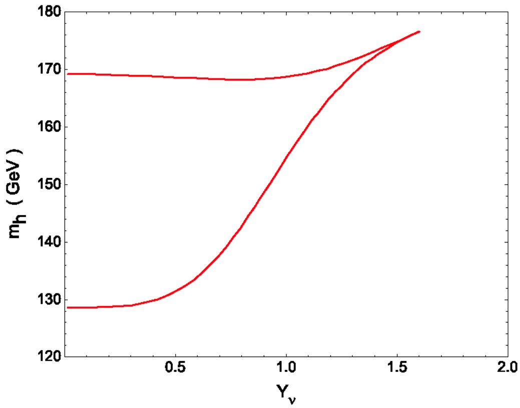

FIGURE 2. Higgs boson mass bound as a function of Y_ν. The lower and upper lines correspond to the stability and perturbativity bounds, respectively. The limit $Y_\nu = 0$ reproduces the SM result. The Higgs boson mass range is closed for $Y_\nu \simeq 1.6$.

needed to explain the observed atmospheric and solar neutrino oscillations. It is relatively straightforward to fix this problem by introducing three SM singlet (right-handed) neutrinos which help generate the desired light neutrino masses via the seesaw mechanism. I will not discuss the seesaw mechanism here but in Fig. 2 it is shown how the SM Higgs bound in Fig. 1 can be impacted by the presence of the new Yukawa coupling Y_ν which links the Higgs field, the lepton doublet and the right handed neutrino. Note that I am assuming here that only the third generation coupling plays an important role in the renormalization group analysis . For $Y_\nu = 0$ one reproduces the results of Fig. 1. Note that the Higgs mass window is closed for $Y_\nu = 1.6$ which corresponds to $m_h = 175$ GeV. For more details and additional references see a forthcoming paper by Gogoladze, Okada and Shafi [1].

SM+GENERAL RELATIVITY

Neutrino physics is by no means the sole reason for thinking that there is life (new physics) beyond the SM. The merger of the SM with Einstein's general relativity leads to the highly successful 'hot big bang cosmology' with some remarkable predictions. These include :

- Existence of blackbody radiation with a temperature of 2.725 K ;
- Redshift of galaxies;
- Nucleosynthesis.

However, the big bang cosmology fails to explain many other observations:

- Isotropy of the microwave background;

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- Anisotropies in the microwave background of order 10^{-5} (or so); origin of primordial density fluctuations;
- Baryon asymmetry $\left(n_B/s \sim 10^{-10}\right)$;
- Non-baryonic dark matter ($\Omega_{CDM} \approx 0.25$).

An inflationary cosmology provides the most plausible extension for overcoming some of these problems , and it turns out that new physics beyond the SM is needed to implement primordial inflation. Note that I am adopting what appears to me to be a conservative viewpoint here that modification of gravity is not required by the conundrums listed above. I have left out the fundamental issue of dark energy which is estimated by recent observations to be the dominant component today of the universe energy density. The simplest explanation is to introduce an appropriate cosmological constant term in Einstein's equations.

Before proceeding further let us list a few additional reasons for thinking about new physics beyond the SM:

- Gauge hierarchy problem (in the SM one encounters quadratic divergences in the Higgs sector so that fine tuning is needed to arrange $M_W \ll M_{Planck}$) ;
  There is no explanation in the SM for the observed hierarchical masses and mixings in the charged fermion sector and for the large mixings observed in the neutrino sector;
- Quantization of electric charge is not explained in the SM. Same holds for family replication;

SUPERSYMMETRY

MSSM

It is well known that low energy supersymmetry (SUSY) provides one of the most compelling extensions of the standard model. Here are some good reasons for this assertion based on the minimal supersymmetric standard model (MSSM) with TeV scale supersymmetry:

- Resolution (at least partial) of the gauge hierarchy problem;
- The three gauge couplings of the SM merge together at an energy scale of order 2×10^{16} GeV . This suggests SUSY grand unification which also then would explain electric charge quantization;
- The lightest supersymmetric particle due to R-parity is stable , and if it is also electrically neutral, is a highly plausible cold dark matter candidate (LSP.

One of the most attractive features of low energy SUSY is that it predicts a plethora of new particles and at least some, hopefully, will be discovered at the LHC. The MSSM features a pair of electroweak (EW) doublets and it seems reasonable to expect that the lightest CP even Higgs scalar h will be found at the LHC. Including radiative corrections, its mass is given by

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta \left(1 - \frac{3}{8\pi^2}\frac{m_t^2}{v^2} t\right) + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}$$

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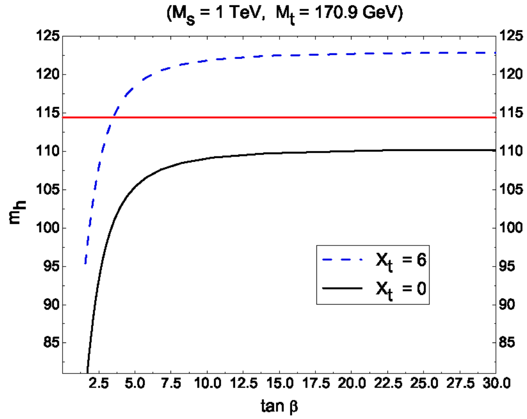

FIGURE 3. MSSM Higgs bounds

$$\times \left[\frac{1}{2} X_t + t + \frac{1}{16\pi^2} \left(\frac{3}{2} \frac{m_t^2}{v^2} - 32\pi\alpha_s \right) \left(X_t t + t^2 \right) \right] \tag{7}$$

where

$$t = \log \frac{M_S^2}{m_t^2},\ \widetilde{A}_t = A_t - \mu \cot\beta,\ X_t = \frac{2\widetilde{A}_t^2}{M_S^2} \left(1 - \frac{\widetilde{A}_t^2}{12 M_S^2} \right). \tag{8}$$

Here $M_S \sim$ TeV denotes the SUSY breaking scale and A_t is the coefficient of the soft SUSY breaking trilinear term. Fig. 3 shows the dependence of m_h on $tan\beta$, the ratio of the two EW doublet vevs. With a top quark mass of 170.9 GeV or so, it is hard to achieve a value for m_h in excess of about 125 GeV.

CMSSM

Next let us briefly discuss the so-called constrained minimal supersymmetric model (CMSSM) which has been extensively discussed in the literature. Here one makes a plausible assumption , motivated to a large extent by supergravity (SUGRA), that the soft SUSY breaking parameters of the MSSM acquire universal values at some suitably high scale, say $M_{GUT} \sim 2 \times 10^{16}$ GeV. The CMSSM consists of five parameters:

$$m_0,\ \ m_{1/2},\ \ A_0,\ \ \tan\beta,\ \ \text{sign}\mu \tag{9}$$

where
m_0 = Universal soft SUSY breaking scalar mass
$m_{1/2}$ = Universal SSB gaugino mass
A_0 = Universal SSB trilinear interaction
$\tan\beta = \frac{v_u}{v_d}$
μ = Supersymmetric bilinear Higgs parameter

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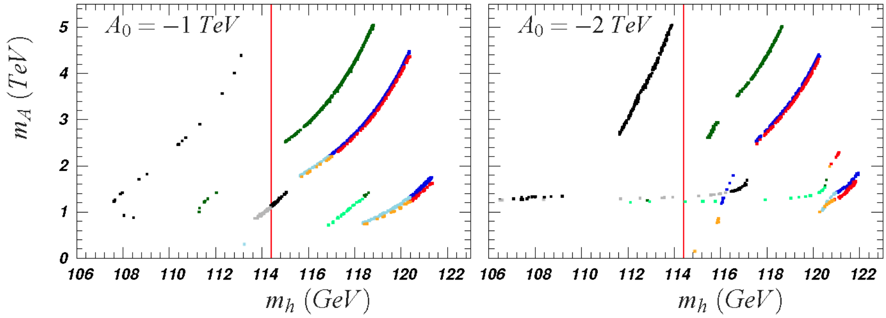

FIGURE 4. Allowed region for CP-odd Higgs boson mass m_A versus m_h. Gray, light green, light blue, and orange correspond to $\tan\beta$ =5, 10, 50 and 53 respectively and satisfy the 3σ bound on Δa_μ. Black, dark green, blue and red correspond to $\tan\beta$ =5, 10, 50 and 53, with Δa_μ outside the 3σ range.

To find mass bounds on the Higgs and sparticle masses and explore possible correlations between them, we have performed random scans using the ISAJET 7.74 package for the following range of the CMSSM parameters:

$$0 \leq m_0 \leq 5\,\text{TeV}, 0 \leq m_{1/2} \leq 2\text{TeV}$$
$$A_0 = 0.5\,\text{TeV},\ 0,\ -1\,\text{TeV},\ -2\,\text{TeV}, \tan\beta = 5,\ 10,\ 50 \text{ and } 53 \qquad (10)$$

with $\mu > 0$ and $m_t = 171.4$ GeV. In performing the analysis we have taken the following constraints into account:

- Radiative EW breaking;
- $m_h \geq 114.4$ GeV (LEP II bound);
- Lightest chargino mass > 103 GeV ;
- Ω_{CDM} consistent with WMAP observations ($\Omega_{\text{CDM}}h^2 = 0.111^{+0.011}_{-0.015}$, (2σ));
- $2.85 \times 10^{-4} \leq Br(b \to s\gamma) \leq 4.24 \times 10^{-4}$;
- $BF(B_s \to \mu^+\mu^-) < 1.0 \times 10^{-7}$;
- $3.4 \times 10^{-10} \leq \Delta a_\mu \leq 55.6 \times 10^{-10}$(where $a_\mu = \frac{(g-2)_\mu}{2}$);

Some of the results are displayed in Fig.4 and Fig.5 (for more details see [2]). A few comments are in order. A large chunk of the CMSSM parameter space is excluded by the WMAP dark matter constraints. The CP-odd scalar A is expected to have a mass in excess of about 200 GeV. Similarly, the gluino mass is estimated to be larger than about 450 GeV.

EXTRA DIMENSIONAL THEORIES

The best motivation today for higher (extra) dimensional theories comes from string theory according to which the universe may have six or even seven additional spatial dimensions which so far have escaped experimental detection. String theory provides it

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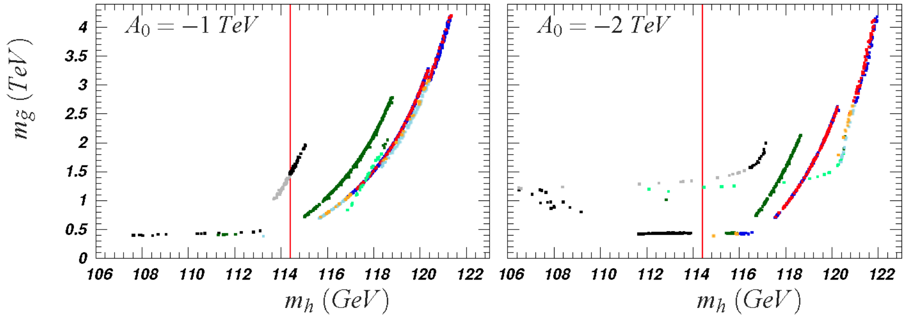

FIGURE 5. Allowed region for gluino mass versus m_h. The color code is the same as in Fig. 4.

seems the most compelling framework for unifying Einstein's gravity with the SM . If all of the extra dimensions happen to be tiny ($\sim$ Planck length) and flat, then it is most unlikely that we can 'directly' detect them experimentally.

To 'observe' one or more extra dimensions we need a great deal of cooperation from nature. Briefly, here are two options which have been extensively discussed in recent years:

Large(submillimeter size or less) Extra Dimension(s)

The scale for quantum gravity is assumed to be of order TeV, with only gravity propagating in the extra dimension(s). This bold conjecture faces serious challenges from astrophysics and cosmology but remains viable at some level. It was meant to resolve the gauge hierarchy problem but this has not been adequately demonstrated. If one or more large extra dimension is found at the LHC it would be truly remarkable and it may signal the onset of TeV scale quantum gravity. The odds for this occuring though are not terribly high.

Warped Extra Dimension

This approach attempts to resolve the gauge hierarchy problem without the introduction of a large extra dimension (See [3]). It relies on a 5D non-factorizable geometry

$$ds^2 = e^{-2\sigma(y)}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2, \tag{11}$$

where $\sigma(y) = k|y|$. The 4-dimensional metric is $\eta_{\mu\nu} = \mathrm{diag}(-1,1,1,1)$, k is the AdS curvature, and y denotes the fifth dimension. This metric results from a suitable adjustment of the bulk cosmological constant and the tensions of the two 3-branes which reside at the S_1/Z_2 orbifold fixed points $y = 0, y = \pi R$. Because of the exponential ("warp") factor, the effective mass scale on the brane located at $y = \pi R$ is $M_P e^{-\pi kR}$. If $kR \sim 11$ this scale will be $\mathscr{O}$(TeV), and the brane is referred to as the 'TeV-brane'. Hence the model can generate an exponential hierarchy of scales from a small extra dimension.

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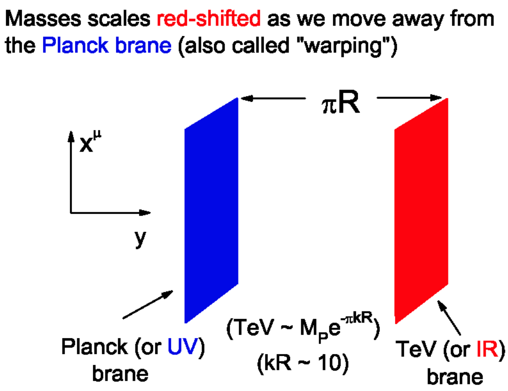

FIGURE 6. Branes in AdS Space

There are two distinct scenarios that one could consider:

- Only gravity propagates in the bulk, while the SM fields reside on the TeV brane. This approach predicts the existence of TeV scale massive gravitinos , but has to cope with several serious issues such as flavor changing neutral currents, proton stability , etc. These problems arise because of the low cutoff scale (TeV).
- In the second (more popular) approach the SM fields (except for the Higgs boson) , just like gravity, also propagate in the bulk. The most interesting consequence of this extension is the appearance of Kaluza-Klein (KK) excitations of the SM particles in the TeV mass range (See Fig. 7).

It is natural to ask whether these KK excitations can be observed at the LHC ?

This is where things start to become a bit complicated. In the simplest models with just the SM fields , the lightest KK excitations of the SM gauge bosons are expected to be in the 7-10 TeV mass range. This constraint arises by confronting the model with precision EW measurements. By considering more elaborate models which go beyond the SM framework it seems possible to achieve KK masses in the range of 2-3 TeV , and this may be more accessible at the LHC.

Let us summarize the salient features of the warped models as follows:

- Bulk SM fields;
- Higgs on the TeV Brane;
- Neutrinos could be Dirac or Majorana;
- Dirac Neutrinos: Introduce SM singlet fermion, (eliminate dim 5 Majorana masses by imposing some symmetry, say lepton number), $\Longrightarrow p$ stable; But $n-\overline{n}$ possible; Also $\mu \rightarrow e\gamma$, etc;
- Smoking Gun: KK excitations at the LHC.

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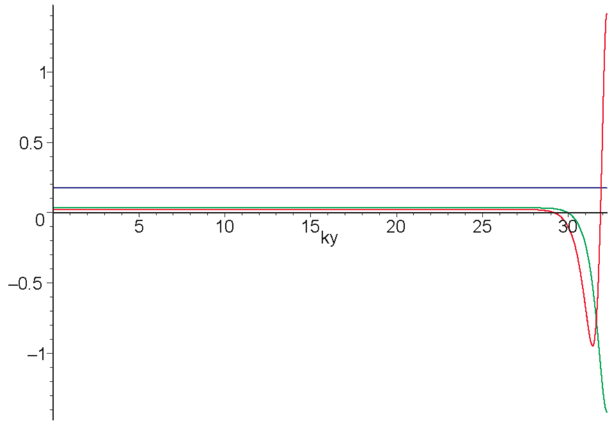

FIGURE 7. KK gauge boson wave functions, showing zero mode (blue), the first (green) and second (red) excited states.

CONCLUSION

The importance of the LHC for the future of high energy physics cannot be overemphasized. Some of the most interesting/ well motivated topics include:

- Electroweak Symmetry Breaking (Higgs, Technicolor, ...)
- Supersymmetry
- Dark Matter (LSP)
- Extra Dimensions (Kaluza Klein excitations)
- Spontaneous Parity Violation (New gauge bosons, other TeV scale particles)
- TeV Scale Quantum Gravity (Black holes,...)
- Exotic States (Magnetic Monopoles, Fractionally charged color singlets, Z flux tubes, Leptoquarks, ...).

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