Proposal for Snowmass2021

Testing High Scale Models at a 100 TeV Collider[1]

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Abstract: SUGRA/string models provide a framework for the extrapolation of particle physics phenomena from the electroweak scale to high scales such as the grand unification scale or the string scale. A common element in such high scale models is the prediction of sparticles which must be seen at colliders. However, the discovery of the Higgs boson mass at 125 GeV indicates that the size of weak scale SUSY is large and lying in the TeV region which in part explains the lack of observation of sparticles thus far. It is likely that HL-LHC with an optimal amount of data will do a more efficient job on decyphering the compressed spectrum and discover a sparticle or two. In such a circumstance, a full fledged search for all the remaining particles and of heavier Higgs bosons and measurement of their couplings would be central to establish the underlying unification. A 100 TeV collider would be an ideal machine for such an endeavor. Recently the CERN Council has updated its strategy for the future of particle physics in Europe and indicated a bold initiative for a 100 TeV hadron collider[4] possibly preceded by an e^+e^- Higgs factory. As noted above a 100 TeV collider will be an ideal machine for the discovery of sparticles and of heavier Higgs and test their properties. In addition, the collider would allow possible discovery of dark matter, of hidden sectors and allow one to discover the nature of radiative breaking of the electroweak symmetry, i.e, if such breaking takes place on the ellipsoidal branch or on the hyperbolic branch.

Discussion: The discovery of the Higgs boson at $\sim$ 125 GeV indicates that the size of weak scale supersymmetry is higher than what was perceived in the pre-Higgs boson discovery era and lies in the several TeV region [1]. Additionally quite typically in models with a high SUSY scale one needs coannihilation which requires the NLSP to lie close to the LSP leading to SUSY signatures involving soft jets and leptons which are difficult to detect [2]. This makes the observation of sparticles with high mass more challenging. In view of the above, the non-observation of supersymmetry thus far is not surprising. Further, from a theoretical view point a large value of the SUSY weak scale has several attractive features: Thus SUSY models have new CP violating phases which can generate very large EDMs for the quarks and for the leptons if the squark and slepton masses are in the sub-TeV region. A solution to this problem requires fine tuning, or a cancellation mechanism [3]. However, if the squark and slepton masses are large, one has a more natural suppression of the EDM consistent with experiment [4]. Another potential problem for a low size of weak scale supersymmetry concerns proton decay from baryon and lepton number violating dimension five operators [5]. For low values of the SUSY weak scale, a suppression of this operator again requires a fine tuning but for high values of the SUSY weak scale lying in the several TeV region this suppression is more easily accomplished [6]. Additionally a high value of SUSY weak scale solves the well known gravitino problem which now will have a mass in the high TeV region and will decay before the BBN. We also note that the unification of gauge coupling constants is satisfied

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[4]From CERN Courier, June 2020: “To prepare for the longer term, the ESPPU prioritizes that Europe, together with its international partners, explore the technical and financial feasibility of a future proton-proton collider at CERN with a centre-of-mass energy of at least 100 TeV.”

to a better degree of accuracy in models with scalar masses lying in the tens of TeV relative to the case when they lie in the sub-TeV region [1]. The High Luminosity LHC (HL-LHC) which will operate at 14 TeV and collect up to 3000 fb^{-1} of integrated luminosity has a good chance of observing one or more of the supersymmetric particles. If that is the case that would be compelling reason to build a collider which has a reach beyond the LHC, to find the rest of the sparticles, determine their couplings and test a variety of high scale models, e.g., supergravity grand unified models [7] and string based models. But regardless of whether the LHC finds a sparticle or two, the search for SUSY/SUGRA must continue as it is a paradigm which extrapolates physics from the electroweak scale to the grand unification scale. Discovery of SUSY/SUGRA is also essential for the eventual test of string theory as SUSY/SUGRA is a natural prediction of superstring theory.

As is well known, the Future Circular Collider (FCC) study group at CERN has been investigating the feasibility of a 100 TeV hadron collider to be installed in a 100 km tunnel in the Lake Geneva basin. The possibility that the 100 km tunnel could be used for e^+e^- machine is also under discussion. Another 100 km collider being considered in China is the Super proton-proton Collider (SppC). A third possibility recently discussed is the High-Energy LHC (HE-LHC) which would use the existing CERN tunnel but achieve a center-of-mass energy of 27 TeV by using FCC magnet technology at significantly higher luminosity than at the HL-LHC. CERN had a dedicated study devoted to this possibility [8, 9] and the authors have contributed to this study [10, 11, 12, 13]. In this study we investigated the potential of HE-LHC for the discovery of supersymmetry and of heavier Higgs which arise is supersymmetric models. Here we discussed a class of supergravity unified models under the Higgs boson mass constraint and the dark matter relic density constraint and compared the analysis with the potential reach of the HL-LHC. A set of benchmarks were presented which are beyond the discovery potential of HL-LHC but are discoverable at HE-LHC. For comparison, we study model points at HE-LHC which are also discoverable at HL-LHC. For these model points, it is found that their discovery would require a HL-LHC run between 5−8 years while the same parameter points can be discovered in a period of few weeks to ~ 1.5 yr at HE-LHC running at its optimal luminosity of 2.5×10^{35} cm^{-2} s^{-1}. Another area investigated was long-lived particles which can arise in certain regions of the MSSM/SUGRA parameter space. In the models investigated it was seen that for the parameter points which are discoverable both at HL-LHC and HE-LHC, the discovery at HE-LHC occurs in a much shorter period of time. Further, of course the mass reach of HE-LHC is significantly larger as expected.

We propose that a similar study for a 100 TeV collider for Snowmass2021 for theoretically well motivated models such as SUGRA and string based models is timely. Several studies of physics at a 100 TeV machine already exist [14, 15, 16, 17]. While these studies are important regarding the landscape of models one can encompass, more focused studies to discriminate among theory models are needed to explore the nature of UV physics we can glean from them. The studies could include: (i) The reach of the 100 TeV collider for sparticles and for heavy Higgs, (ii) The specific signature channels most likely to lead to a discovery in the context of specific models, (iii) What one may learn regarding the nature of dark matter, (iii) The nature of electroweak symmetry breaking to determine whether it exists on the ellipsoidal branch or on the hyperbolic branch [18] of radiative breaking. (iv) A study of pile-up which is basic to extracting any new physics at the 100 TeV. The FCC panel indicates that the 100 TeV collider might be preceded by an e^+e^- machine. While such a machine would mainly be a Higgs factory, there is a part of the SUGRA parameter space with small μ which could lead to heavier Higgs bosons within reach of the e^+e^- machine. A small μ arises naturally on the hyperbolic branch of radiative breaking of the electroweak symmetry in SUGRA models [18] which would result in relatively light Higgs accessible at the e^+e^- machine.

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