論文の内容の要旨

Aspects of Supersymmetry after LHC Run I
(LHC Run Iを踏まえた超対称性理論の諸問題)

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Supersymmetry (SUSY) is a prime candidate for physics beyond the Standard Model, and we investigate aspects of supersymmetry in light of Large Hadron Collider (LHC) results. The main accomplishment of LHC Run I is discovery of Higgs boson, and it is a momentous step towards understanding electroweak symmetry breaking. The Standard Model Higgs sector, however, is not theoretically satisfactory. Since the Higgs mass scale is not protected by any symmetry, the electroweak scale is unstable to be at observed scale and hence unacceptable fine-tuning is required. Unlike the Standard Model, low-energy supersymmetry stabilizes the Higgs mass avoiding fine-tuning and leads to natural electroweak symmetry breaking. The natural scale of supersymmetric particles (sparticles) is below $\approx$ TeV. The minimal supersymmetric Standard Model (MSSM) has been studied, and it was found the lightest supersymmetric particle (LSP) is a good dark matter candidate.

However, there are tensions between low-energy supersymmetry and the LHC results. Firstly, searches at the LHC for sparticles have not found any signal and give strong limits on mass of gluino and squark up to ≈ 1.8 TeV for a conventional model, constrained minimal supersymmetric Standard Model (CMSSM). Next, the observed Higgs mass of 125 GeV is not easily accommodated in the MSSM, where one has to rely on the radiative corrections to boost the Higgs mass beyond the tree-level upper bound of $m_Z \simeq 91$ GeV. This requirement push sparticles scale well beyond the TeV within CMSSM, leading to fine-tuning. In this thesis we particularly study two scenarios of supersymmetry originating the tensions.

A nearly degenerate (compressed) spectrum ameliorates the bounds from the current searches at the LHC whereas the CMSSM typically generates a widely spread spectrum. For the lack of SUSY signal, the scenario with a compressed spectrum recently has more attentions, but motivations and explicit models for the scenario have not been discussed. Therefore we study this direction in detail.

Supersymmetry broken geometrically in extra dimensions, by the Scherk-Schwartz mechanism, naturally leads to a compressed spectrum. We present a minimal such model with a single extra dimension, which we call “Compact Supersymmetry,” and show that it leads to viable phenomenology despite the fact that it essentially has two less free parameters than the CMSSM. The theory does not suffer from the supersymmetric flavor or CP problem because of universality of geometric breaking, and automatically yields near-maximal mixing in the scalar top sector with $|A_t| \approx 2m_{\tilde{t}}$ to boost the Higgs boson mass. Despite the rather constrained structure, the theory is less fine-tuned than many supersymmetric models. The LSP is Higgsino-like and can be a component of dark matter. We find direct detection experiments will cover a large portion of parameter space. The collider constraint on the Compact Supersymmetry is certainly weaker than that on the CMSSM as gluino and squark mass bound is relaxed down to ≈ 1 TeV. In order to increase sensitivity to models with a compressed spectrum, we suggest a kinematic variable, M_{T2}, can be useful since the Standard Model background is systematically removed by requiring $M_{T2} > m_{\rm top}$.

Naturalness implies new dynamics beyond the minimal theory. There have been many attempts to extend the MSSM to accommodate the Higgs mass. In such extensions, new states interact with the Higgs, raising its mass by increasing the strength of the quartic interaction of the scalar potential. One possibility is a non-decoupling F-term, as in the NMSSM (MSSM plus a singlet S). If the new states are integrated out supersymmetrically, their effects decouple and the Higgs mass is not increased. On the other hand, SUSY breaking can lead to non-decoupling effects that increase the Higgs mass. However, in general, these extensions require new states at the few hundred GeV scale, so that the new sources of SUSY breaking do not spoil naturalness.

In this thesis, we have identified a new model where the Higgs couples to two singlet fields with a Dirac mass, which we call Dirac NMSSM,

$$W \supset \lambda S H_u H_d + M S \bar{S}.$$

The non-decoupling F-term increases the Higgs mass while maintaining naturalness even in the presence of large SUSY breaking in the singlet sector as $m_{\bar{S}} \gtrsim 10$ TeV. The key feature in the Dirac NMSSM is that $\bar{S}$ couples to the MSSM only through the dimensionful Dirac mass, M. We note that interactions between $\bar{S}$ and other new states are not constrained by naturalness, even if these states experience SUSY breaking. Therefore, the Dirac NMSSM represents a new type of portal, whereby our sector can interact with new sectors, with large SUSY breaking, without spoiling naturalness in our sector.

Collider signatures of the Dirac NMSSM are discussed. The low-energy phenomenology is that of a two Higgs doublet model. We obtain constraints from direct searches for heavier Higgs boson and coupling measurements for the lightest Higgs boson at the LHC. We also study the future reach based on prospects of high-luminosity LHC and future international linear collider, and show large parameter space can be probed.