Search for Weak Scale Supersymmetric Particles in Compressed Scenarios

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Abstract

This is the abstract

Acknowledgements

Thanks everybody

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Chapter 1

Motivating the Search for SUSY

1.1 Introduction

The SM is a remarkable theory which describes a wide variety of sub-atomic phenomenon and has consistently held up to tests over many orders of magnitude in energy. However, it's not a perfect theory. There are a few experimental and theoretical problems that the SM can not yet explain like: how to incorporate gravity, how can we explain neutrino mass and mass orderings, why is the universe made up of matter and not antimatter? Observations from the relic microwave background suggest the existence of cold dark matter (cite DM observation), but, there are no suitable SM dark matter candidates to explain the abundance of dark matter. SUSY offers many attractive solutions with the introduction of new particles. One such new particle which can serve as a mediator of gravitational interactions is the gravitino.. Other examples include massive invisible particles which act as dark matter candidates such as the neutralino, χ_1^0. The neutralino can handle the DM problem with models capable of producing the expected relic DM density of the universe and, in fact, the DM relic density is used to constrain the SUSY model space and simplify searches. Aside from these leading motivations, other more detailed motivations will be discussed in this chapter, the first being the "naturalness problem" with its theoretically aesthetic improvement which adds a symmetry to protect against divergent terms in the perturbative expansion of the Higgs mass. The next motivations are experimental, where SUSY offers an explanation to the signficant deviation observed in the muon $(g-2)$ factor from recent FNAL result, as well as the deviation observed in the W boson mass at CDF. It should be noted that the divergent higgs mass - known as the hierarchy problem - satisfies most SUSY scenarios up to the few TeV scale, but, the two latter experimental measurements motivate searching for SUSY in compressed scenarios.

1.1.1 Stabilizing the Higgs mass

An aesthetic attribute of theoretical models is naturalness, we should expect a model to function "naturally" if the ratio of free parameters in a model are of $O(1)$. Large swings between parameters would be considered fine-tuning and could indicate issues with the underlying theory. So, naturally, if fine-tuning exists in a model, it strongly motivates building extensions to the model to eliminate fine-tuning. One such fine tuning arises in the hierarchy problem, specifically in the Higgs self interaction terms. The SM Higgs Lagrangian terms that involve self interaction are illustrated in equation 2.1.

$$\mathcal{L} = \frac{gm_h}{4M_W}H^3 - \frac{g^2m_h^2}{32M_W^2}H^4 \tag{1.1}$$

H represents the scalar higgs field, m_h the higgs mass, and m_W the W boson mass. A correction to the higgs mass can be calculated using standard perturbation theory by evaluating the second term of the Higgs Lagrangian. (cite baer)

$$\begin{aligned}\Delta m_h^2 = \langle H|\frac{g^2m_h^2}{32M_W^2}H^4|H\rangle &= 12\frac{g^2m_h^2}{32M_W^2}\int\frac{d^4k}{(2\pi)^2}\frac{i}{k^2-m_h^2} \\ &= 12\frac{g^2m_h^2}{32M_W^2}\frac{1}{16\pi^2}\big(\Lambda^2 - m_h^2\log\frac{\Lambda^2}{m_h^2} + O(\frac{1}{\Lambda^2})\big)\end{aligned} \tag{1.2}$$

Here the intergal term is the propagator (cite propagator stuff??) for the exchange of a virtual Higgs and is integrated over phase space. The Λ is known as the scale cutoff parameter and should be interpreted as the scale at which the SM breaks down, possibly near the planck scale $O(10^{19})$GeV. Notice the leading term Λ^2 indicates that the expansion is quadratically divergent. The divergent mass correction means there needs to be extremely large cancellations, around 20 orders of magnitude, to maintain $\Delta m_h \propto O(m_h)$. This divergent phenomenon can also be observed with fermion masses, but, chiral symmetry protects the fermion mass from divergence by cancelling out high order Λ terms. SUSY offers a similar protection to the Higgs mass by introducing a symmetry with the additional fermionic and bosonic degrees of freedom leading to similar cancellations and a more natural model.

1.1.2 The Muon Anomalous Magnetic Moment

A major experimental motivation for SUSY lies within the measurement of the muon anomalous magnetic moment. Multiple meausurements between two labs, Brookhaven National Lab (BNL) and Fermi National Accelerator Lab (FNAL) have shown significant disagreement with the SM. These experiments measure the muon g factor, or specifically, its deviation from two, $(g-2)_\mu$. The g factor is related to the electromagnetic coupling of charged particles with the photon and largely depends on the tree level lepton-photon coupling, but, gets small quantum corrections from higher order loops. The largest correction being the single photon loop shown in Figure 2.1. To predict the g factor, an SM calculation is performed with three types of quantum corrections: Quantum Electrodynamic (QED), Electroweak (EW), and Hadronic. Corrections from the Higgs are neglected because the effects are not experimentally observable. The g-factor prediction starts at exactly 2, with QED, and then involves quantum corrections up to $O(10^{-11})$. The prediction is compared with an experimental measurement at a very high level of precision. If the observation were to deviate from the SM prediction, it can indicate new and unaccounted physics interactions with the SM leptons. The current best $a_\mu = \frac{g-2}{2}$ prediction is reported as $a_\mu = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{\text{Hadronic}} = 116591810(43) \times 10^{-11}$. For each of the a_μ components, the QED compenent enters at the $O(10^{-3})$ and is known to $O(10^{-11})$. the EW component enters the sum at $O(10^{-9})$ and is known to $O(10^{-10})$. Finally the most complicated hadronic component, contributes at $O(10^{-8})$ and is known up to $O(10^{-9})$. The hadronic contributions arise from Hadronic vacuum polarization(HVP) and light by light scattering with the HVP

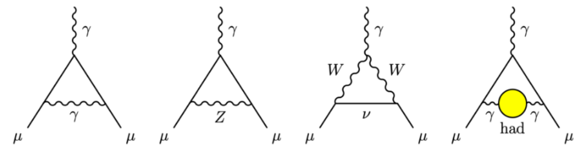


Figure 1.1: figures from https://www.particlebites.com/?p=8972 which cites pdg

diagram also illustrated in Figure 2.1. The a_μ^{Hadronic} precision dominiates the overall a_μ error and is constrained by data driven measurements alongside the limitations of the computational approach with QCD lattice theory. The BNL measurement of a_μ yields a difference with the SM prediction of $\Delta a_\mu := a_\mu^{BNL} - a_\mu^{SM} = 279(76) \times 10^{-11}$ which carries significance of 3.7σ. The most recent a_μ measurement from FNAL confirms the BNL measurement within 1σ and the combined experimental average increases the SM deviation with a significance of 4.2σ.

The 4.2σ is a compeling sign for new physics, but not a smoking gun. It is possible to reduced or eliminate the discrepancy by improving the calculations of the HVP and LBL contributions. An early attempt resolve the discrepancy was done by the BMW group and eases the tension to 1.2σ (cite BMW) but still does not fully resolve the differences between observations and theory. If computational improvements can't bring the theory into focus, new particles introduce quantum corrections that will bring experiment and theory into agreement. Several models qualify and successfully explain the a_μ SM deviation, one being SUSY, where for example, contributes additional diagrams via the smuon-muon coupling illustrated in Figure 2.2.

Figure 1.2: SUSY diagrams explaining g-2 from svens talk

1.1.3 The W boson mass

The W boson is an important and peculiar particle, it is the electrically charged boson and couples only with left handed particles. The decay modes follow two channels: (1) the hadronic mode with different flavor quark pairs and (2) the leptonic mode with a charged lepton and neutrino. Measuring the W mass directly is challenging at the LHC due to either high levels of QCD di-jet background or missing energy from the neutrino. The mass parameter itself, m_W, underpins many important parameters in the SM as well. In fact, m_W is related to the Higgs vev, which implies that coupling of the higg field to all particles is effectively tuned by m_W. Similary, m_W is related to the g factor from $(g-2)_\ell$ such that $m_W = gv/2$. The W mass can also be paramterized at tree level in terms the fine structure constant α, the Fermi constant G_μ and the Z-boson mass m_Z, with higher order radiative corrections coming from Δr (cite w mass prediction paper)

$$m_W^2 = m_Z^2\left(\frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\pi\alpha}{\sqrt{2}G_\mu m_Z^2}(1+\Delta r)}\right) \tag{1.3}$$

There is no exact SM prediction of the W mass, but, since there is an interdependence of many parameters such as v, m_z, G_μ,α , the SM "prediction" is constrained by experimentally measured parameters. The most recent measurement of m_W was performed by CDF II at the Tevatron where m_W was obtained by fitting the kinematic distributions of light leptonic decays recoiling against a system of jets. This measurement is 50% more precise than the previous measurement by ATLAS (cite atlas) and heavier than the SM prediction. The combination of a large deviation with very small error bars results in a significance of 7σ. (cite CDFII).

If we believe the CDF measurement, and follow up experiments confirm the excess in the W mass, it is definite sign of new physics. The new physics would express itself as new particles in the radiative corrections via equation 2.3. There are numerous SUSY models that could explain the excessive mass of the W boson, (CDF lightsusy) but in general, a slightly heavier W favors light SUSY models which is illustrated in Figure 2.3. A light SUSY implies models that are characterized by electro-weak scale SUSY particles among which can favor compressed scenarios. The available parameter space, with an abundance of models, where also CDF II's m_W and the $(g-2)_\mu$ can be satisfied is shown in Figure 2.4.

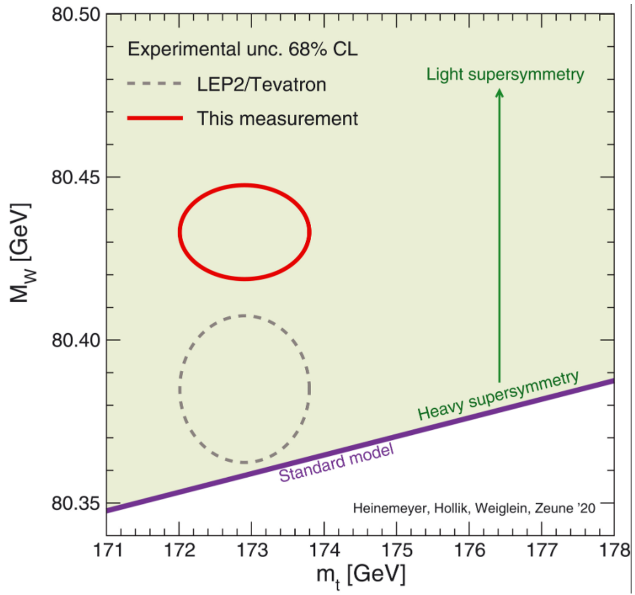


Figure 1.3: plot from CDF paper

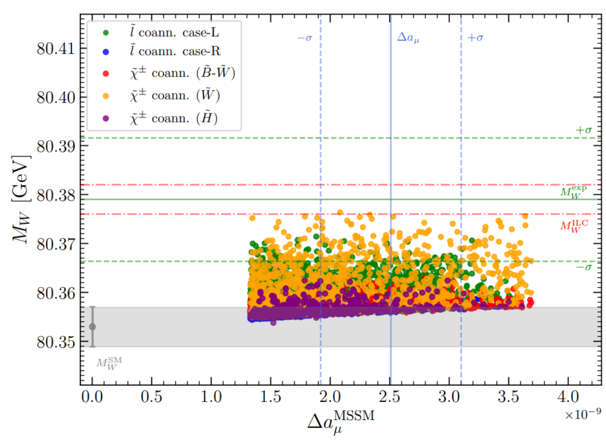


Figure 1.4: sven plot from paper

1.2 The current status of SUSY

There have been many searches for SUSY particles, starting from searches at LEP and still ongoing at the LHC today. There is no observed evidence of SUSY yet, but, there is still not enough lack of observation to fully reject the SUSY hypothesis. The most widely searched region SUSY space is related to strong production of SUSY particles. The large expected cross sections compared to other sectors gauginos/sleptons offers the most low hanging fruit for potential discovery. Simplified models in CMS have excluded $\tilde{g}$ and $\tilde{q}$ up to around 2 TeV with the most recent limits are shown in Figure 2.5. The area inside the lines in Figure 2.5 indicate that the 2-D mass points of the sparticle and LSP pair are ruled at a 95% confidence level. Simlarly the CMS slepton and electroweak limits are shown in Figure 2.6. Note that

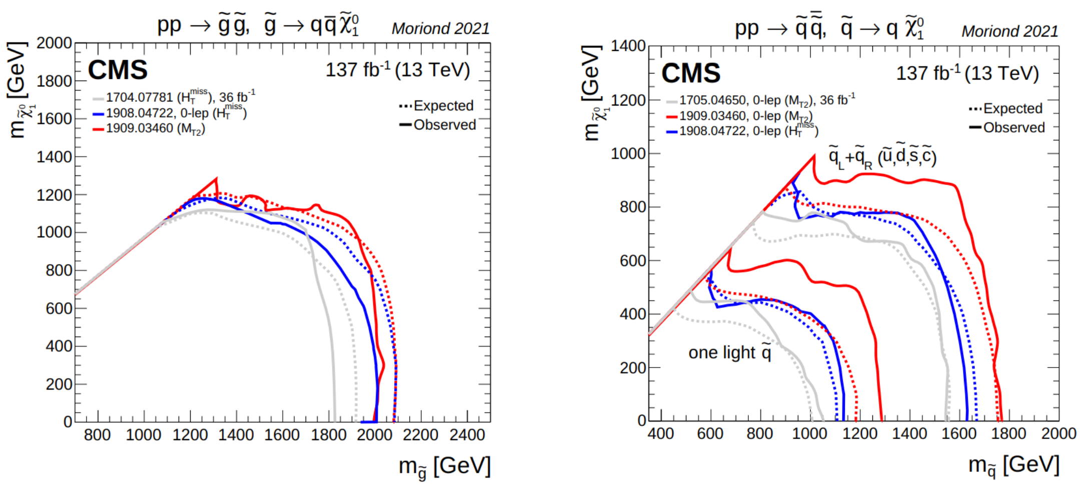
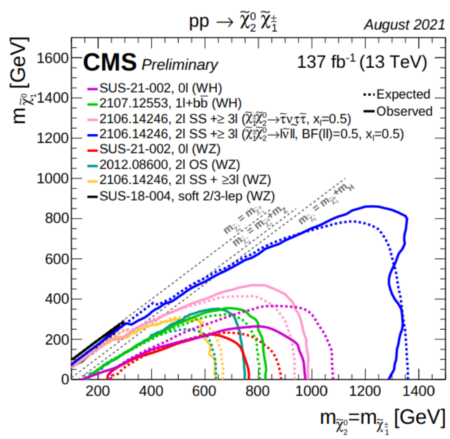


Figure 1.5: strong limits

the electro weak limits are just now reaching the TeV scale while SUSY remains valid at the few TeV level, so, there is plenty of room in the 2-D mass plane to either discover or exclude SUSY by adding more data. Notice also that the corridors with compressed regions for electroweakinos and sleptons are effectively untouched. So, a well motivated region to search is near the LSP-sparticle mass degeneracy line in the 2-D mass plane because it is both unexplored at high masses and theoretically and experimentally well motivated.



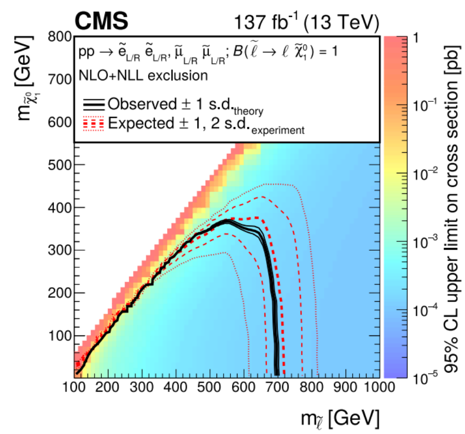


Figure 1.6: limits