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

The Standard Model and Supersymmetry

1.1 Introduction

The fundamental building blocks of matter and their interactions expressed through three of the four fundamental forces of nature via the Standard Model (SM). The fourth force, or gravity, is left to General Relativity. The SM is the culmination of over a century of work by many scientists, and has its roots in the late 19th century. The first force is based on the theory of strong interactions, formulated as quantum chromodynamics by Murray Gell-Mann and others in the 1960s, which provides a description of how protons and neutrons are held together in the nucleus of an atom. The theory describing weak interactions was developed by Enrico Fermi in the 1930s, which was then combined with electromagnetic interactions in electroweak theory by Sheldon Glashow, Abdus Salam, and Steven Weinberg in the 1960s. In this chapter, concepts of the Standard Model are introduced, including the fundamental particles, fields, and their basic properties and interactions. Then expanding from the core SM we will discuss an extension of the Standard Model with supersymmetry, which proposes a new symmetry between fermions and bosons. Finally, we delve into the specifics of simplified models of supersymmetry and the challenges associated with detecting these models experimentally.

1.2 The Standard Model

The Standard Model is a collection of adhoc theories used to predict and reproduce experimental data. The theory itself incorporates four major concepts: Quantum Field theory (QFT), the Dirac equation, the gauge principle, and the Higgs mechanism. These four principles are constrained by physical data and describe the set of elementary particles, known as fermions and bosons. The SM generally refers to the SM Lagrangian, an equation with different sectors that describe different subsets of particles, fields, and their interactions. The SM Lagrangian itself consists of 26 free parameters which are input by hand. These parameters are: the masses of the 12 fermions, 3 coupling constants that describe gauge interactions: g, g', g_s, 2 parameters to desribe the Higgs potential i.e. the higgs mass m_h and the vacuum expectation value (vev), and 9 mixing angles which describe the PMNS and CKM matrices or the mixing of different fermionic fields. The 12 fermion paramters are subdivided by three neutrinos m_{ν_i}, three charged leptons $m^{\pm}_{\ell_i}$, and six quarks m_{q_i};

QFT provides a description for both known and theoretical particles by combining quantum theory, the field concept, and relativity (cite peskin). The gauge theory aspect describes the exact nature of QFT interactions and provides the mechanisms for the electromagnetic, strong, and weak forces. We know of three gauge fields: $\vec{G}$ which transforms under $SU(3)$ and govern strong interactions, $\vec{W}$ and B which transform under $SU(2)_L \times U(1)$ and govern electromagnetic and weak interactions. The combination of the gauge fields and fermion fields along with the Dirac equation yields eigenstates that represent fermionic matter particles. These particles would be massless if not for the inclusion of the complex scalar Higgs field. The spontaneous symmetry breaking of the Higgs field, due to the Yukawa coupling, creates the non-zero vev responsible for generating the masses of the electroweak gauge bosons. Additionally, the interaction between the fermionic fields and the non zero-vev generates the masses of SM fermions.

The set of standard model elementary particles is divided into two subgroups: fermions and bosons. The fermions consist of both charged and neutral leptons as well as fractionally charged quarks. There are three flavors of charged leptons (ℓ), the electron (e), the muon (μ), and the tau (τ). Each charged lepton has a flavor pairing neutral neutrino ν_ℓ. The e and μ are also generally considered as "light" leptons due to their small mass relative to the τ. The term lepton, depending on context, often refers to only the charged particles. As for the quarks, there are also three generations of pairs of quarks.. The lighest set of quarks are the up (u) and down (d) quarks, followed by the charm (c) and strange (s), and lastly the bottom (b) and extremely massive top quark (t). The bosons are the force carrying particles which represent the gauge fields. They are comprised of the vector bosons - the photon (γ), gluon (g), the $W^{\pm}$, and the Z^0 - along with the singular scalar boson the Higgs (h). The elementary particles masses, generations, and spins are summarized in Figure 1.1.

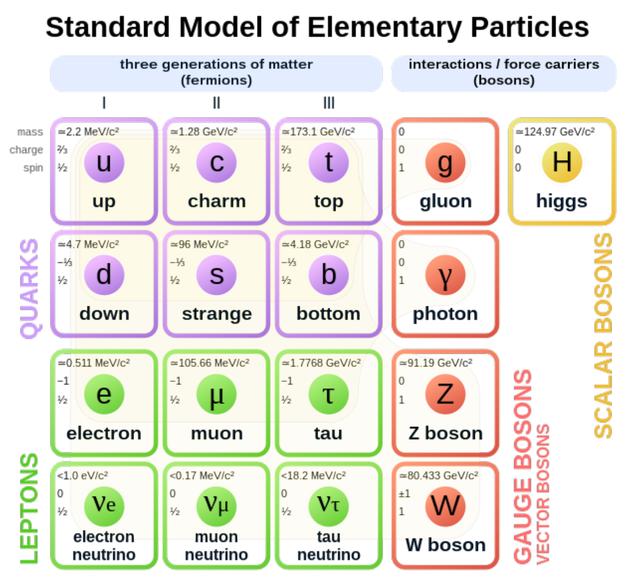

Figure 1.1: particles figure cite wiki

The SM is an asymmetric chiral theory, combining three groups $SU(3)_L \times SU(2)_L \times U(1)$. The L, or left handed, subscript indicates that mirrored fields (with different chiralities) transform differently under the Lorentz group and the EW gauge group (cite slides). The consequence of chiralilty is that the possible combinations between interaction vertices is limited(cite thompson). This peculiar property shows up with the W boson, which only couples to left handed particles or right handed antiparticles. Extensions of the standard model also often extend chiral or symmetrical properties.

1.3 Supersymmetry

Supersymmetry (SUSY) is an extension of the standard model. It adds a generator that rotates the spin between bosons and fermions. This then introduces a bosonic degree of freedom for every fermionic degree of freedom (cite run2 susy paper) which generates a super partner for each particle with spin differing by a half integer. The resulting set of mirrored elementary particles are referred to as sparticles. Each bosonic sparticle carries the same name as its fermion partner but with an "s" prefix e.g. sfermion, squark, selectron. As for the bosons, with the gauge fields B and $\vec{W}$, these are accompanied by three super symmetric fields - the Higgsino $\tilde{H}$, Bino $\tilde{B}$, and Wino $\tilde{W}$. The mixture of the B and $\vec{W}$ SM fields can be represented by particle matrix. One can obtain the mass eigenstates representing the SM particles γ, Z, $W^{\pm}$ through the diagnolization of particle matrix. Similarly, the Higgsino, Bino, and Wino mix to produce four neutral and two charged eignestates, the neutralinos $(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)$ and charginos $(\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm})$ (cite erich's 43 susy matrix eigenstates). SUSY also requires an additional Higgs doublet to give mass to up-type and down-type fermions, (cite this run 2 paper.. reference chasing) leading to five higgs boson states consisting of two charged Higgs and three neutral Higgs. The lightest neutral higgs of the three neutral options represents the SM Higgs boson. The full set of SM particles alonglide their SUSY partners are illustrated in Figure **??**. The addition of another higgs doublet also introduces a second vev. The ratio between the two vev's is commonly denoted as $v_1/v_2 = \tan\beta$ and is an important parameter in experimental searches. Another important bookeeping parameter, similar to lepton number or baryon number conservation, is R-parity. This parameter tallies the total number of SM particles (+1) and sparticles (-1) and expects the net total between particles to be conserved in the initial and final states. R-parity conservation then requires sparticles to be produced in pairs. If R-parity is violated, the common consequence is that the lightest supersymmetric particle (LSP) is unstable.

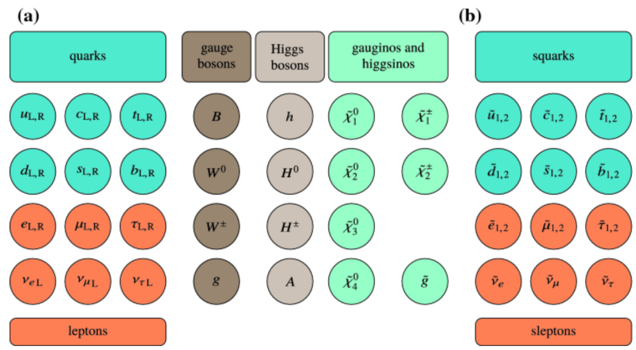

Figure 1.2: stolen from this springer thesis book, probably make my own figure later `https://link.springer.com/chapter/10.1007/978-3-030-25988-4_4`

Supersymmetry is an extremely expansive model and intractable to experimentally test without significant well motivated simplifications. The most experimentally common simplified SUSY model is the Minimally Super Symmetric Standard Model (MSSM). The MSSM contains the smallest number of new particle states and new interactions which are consistent with phenomenology (cite howie direct weak scale book). The MSSM is still experimentally inaccesible due to the presence of over 100 parameters, where small changes in parameter space can completely morph the model structure and experimental signatures. To reduce the problem's dimensionality, further simplification is needed, resulting in a popular simplified model: the phenomological MSSM (pMSSM). The pMSSM contains 19 parameters which include the masses of each generation of squark and slepton, parameters to control the mixing of $\tilde{H}, \tilde{W}, \tilde{B}$, and dials for the higgs doublet(cite what wiki cites). The pMSSM is still borderline too complicated to attack directly, so, the pMSSM is boiled down into a simplified model of four parameters M_1,M_2, μ, and $\tan\beta$. M_1 and M_2 are the gaugino mass parameters, μ is the Higgsino mass parameter, and $\tan\beta$ is the previously mentioned vev ratio (cite Fuks paper). A model point from this four parameter space is referred to as Realistic simplified gaugino-higgsino model, and targets specific regions of MSSM parameter space and experimental topologies.

To effectively grasp the structure of SUSY and various models, either in the pMSSM or simplified models, there are a couple key elements to condsider. The first elements is the mass scale of the relative SUSY sectors i.e. how massive are the gauginos versus sleptons versus squarks. If the mass scales are well separated, the sectors are effectively decoupled. If the mass scales are similar then it may introduce complicated cross-talk between sectors. In an electroweak SUSY search with a 4 parameter simplified model, the model can be further simplified by assuming squarks and slepton masses sit at the several TeV scale while the targeted electroweak-inos are at detectable TeV and sub-TeV scale. By decoupling sectors outside the sector-of-interest we remove the interaction between these groups, so, if sleptons are decoupled from the gauginos complicated dependencies, like cascading decays are avoided. The other key element is the composition of the LSP, typically $\tilde{\chi}_1^0$. Each unique model point is composed of a specific mixing of $\tilde{H}, \tilde{W}, \tilde{B}$ with an LSP that reflects that mixing. The model point is denoted by the field that dominates the overall mix, so a Higgsino model has an LSP composed of mostly $\tilde{H}$ (cite mixing altas paper?). The characteristic take away from simplified model types is that H,W,B can control the nature of the model by governing the overall cross sections for sparticles, the topological infrastructure, and how the sparticles interact and amongst themselves and SM particles. Two pMSSM examples comparing the mass structure between two arbitrary mass points of a Wino model versus Higgsino model is shown in Figure 1.3. For both models the Higgs and slepton sectors are decoupled at a multi-TeV scale while the squark and gaugino sectors are at an accesible TeV and sub-TeV scale. Note that small changes in pMSSM model space results in differing LSP content and large variations in the relative mass structure and orderings. The difference in cross sections between the same two model points for gaugino pair production combinations are show in in Figure 1.4. This relative differences in cross section illustrates that the same tweak in parameter space can induce order of magnitude changes sparticle production.

In addition to the mass structure and cross sections, the decay nature of H/W/B models also varies. The variation in decay modes has a significant impact on the experimental

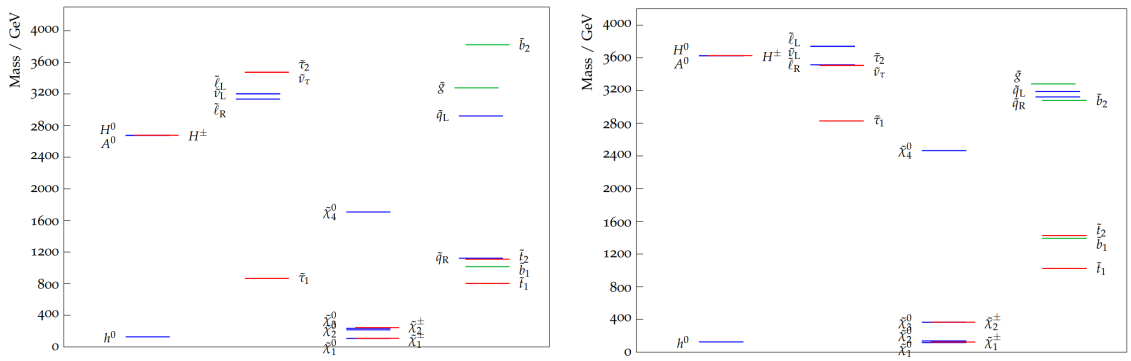

Figure 1.3: mass structure winno vs higgsino modelpoints

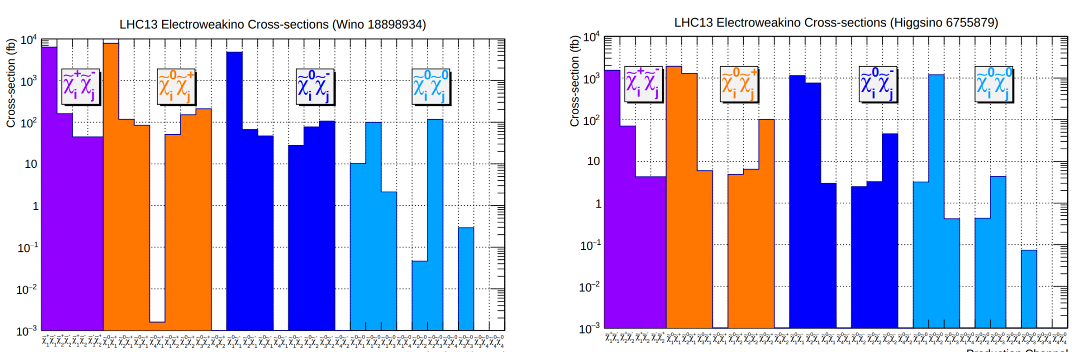

Figure 1.4: xsec strucutre wino vs higgsino modelpoints

channels and signatures of interest. In an experimental search we would expect the heavier sparticles to decay to both SM particles along with the LSP. If the LSP happens to be close in mass to its parent, say O(100) GeV or less, the model would be considered as a compressed scenario. This scenario is considered compressed because the observable energy of the SM particle involved in a sparticle decay is compressed to a very small amount due to the majority of the available energy being used by the rest mass of the sparticles. Of the 3 types of models, the most likely candidates for compression are the Higgsino-like and Bino-like models. Wino models by far have the largest cross sections but are the least likely to have compressed states. Particularly interesting topologies for these compressed models involve decay signatures of processes like $\tilde{\chi}_2^0 \to Z^*\tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^\pm\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$, $\tilde{t} \to t\tilde{\chi}_1^0$, $\tilde{\ell} \to \ell\tilde{\chi}_1^0$. The nature of sparticle decay is not only dependent on the H/W/B nature of the model but also on the degree of compression. Figure 1.5 shows the average decay modes for H W or B from a selection of pMSSM models (cite atlas pmssm paper).

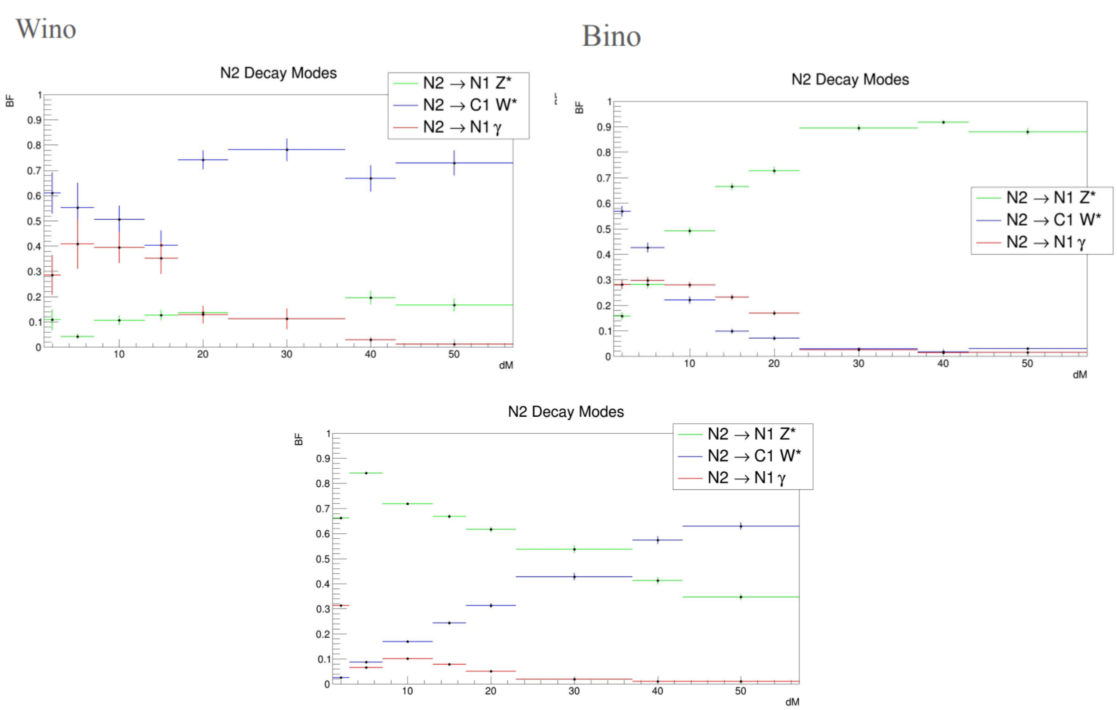

Figure 1.5: N2 BFs

Note that between each model type in Figure 1.5 the Z^* and $W^\pm$ modes can be highly suppressed or enhanced. In some cases even, specific modes like $\tilde{\chi}_2^0 \to \tilde{\chi}_1^{\pm} W^{\mp}$ can be either kinematically forbidden, or excluded to streamline MC production and enhance the statistical power of different targeted final states. Alongside the decay specific complications, the phase space of the final state particles is model dependent. For instance, in the case of $\tilde{\chi}_2^0 \to Z^* \tilde{\chi}_1^0$ the shape of Z dilepton mass distribution $m_{\ell\ell}$ changes depending on the sign of the gaugino eigenstates. Experimentally this problem is divided into two possible scenarios: cases where the eigenstates are the same sign and cases where the eigenstates are the opposite sign. The distribution that showcases the $m_{\ell\ell}$ differences under two different model interpretations is shown in Figure 1.6. Overall, with the complications of model dependent decays, inherently rare production, varying mass orderings, and relative scale between sectors, the search for SUSY is an extraordinary challenge. To discover SUSY one should design a search to encompass a large generalized model space and target generic features rather than highly specific corners.

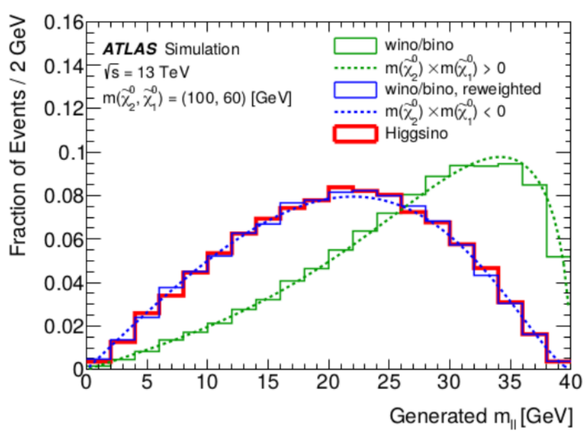

Figure 1.6: mll reweight with w/b or H interpretations from altas paper in grahams talk

Chapter 2

Motivating the Search for SUSY

2.1 Introduction

The SM is a remarkable theory which describes a wide variety of sub-atomic phenomenon. The theory 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 is the gravitino which mediates gravitational interactions. Other examples include massive invisible particles which 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 movitvations are experimental, where SUSY offers an explanation to the signficant deviation observed of the muon $(g-2)$ factor from recent FNAL result, as wells 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.

2.1.1 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 is observed 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.

$$\mathcal{L} = \frac{gm_h}{4M_W}H^3 - \frac{g^2 m_h^2}{32M_W^2}H^4 \tag{2.1}$$

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)

$$\begin{aligned}\Delta m_h^2 = \langle H|\frac{g^2 m_h^2}{32M_W^2}H^4|H\rangle &= 12\frac{g^2 m_h^2}{32M_W^2}\int \frac{d^4k}{(2\pi)^2}\frac{i}{k^2 - m_h^2} \\ &= 12\frac{g^2 m_h^2}{32M_W^2}\frac{1}{16\pi^2}\left(\Lambda^2 - m_h^2 \log\frac{\Lambda^2}{m_h^2} + O(\frac{1}{\Lambda^2})\right)\end{aligned} \tag{2.2}$$

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 natural model.

2.1.2 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 specicially, 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

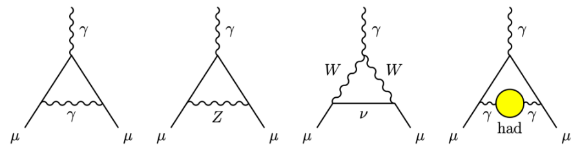

Figure 2.1: figures from https://www.particlebites.com/?p=8972 which cites pdg

arise from Hadronic vacuum polarization(HVP) and light by light scattering with the HVP 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 2.2: SUSY diagrams explaining g-2 from svens talk

2.1.3 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, the hadronic mode with different flavor quark pairs or 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, the 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)

$$m_W^2 = m_Z^2 \left(\frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\pi\alpha}{\sqrt{2} G_\mu m_Z^2}(1+\Delta r)} \right) \tag{2.3}$$

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 lean towards light SUSY implies models characterized by electro weak scale SUSY particles with compressed scenarios are more favorable. The available parameter space where CDF II's m_W and the $(g-2)_\mu$ can be satisfied is shown if Figure 2.4.

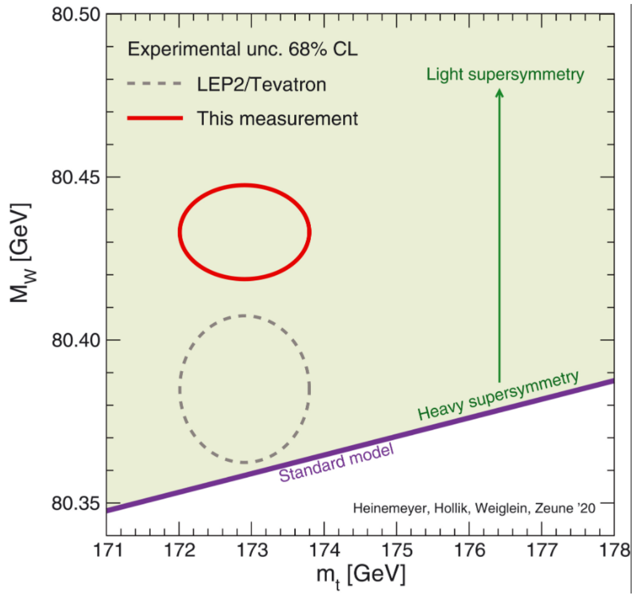

Figure 2.3: plot from CDF paper

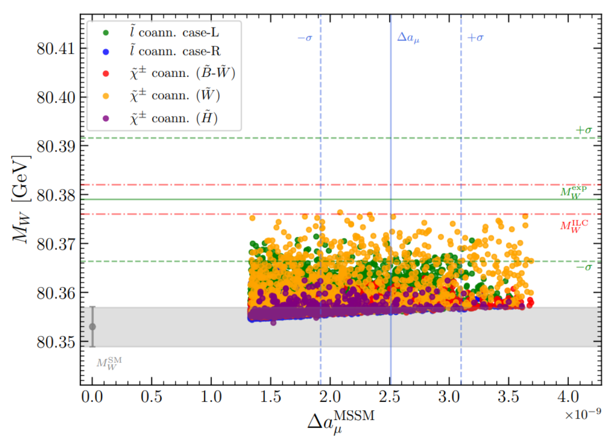

Figure 2.4: sven plot from paper

2.2 The current status of SUSY

drop the most recent limits here, start with multi TeV excluded gluino and squark models which leaves the a good place to search in the weak scale sector with electoweakinos. Talk about electroweak limits and how alot of these are excluded already one of the remaining places to search is the compressed corridor where mass splittings are small. link this limit motivation with how both g-2 and W mass favor compressed scenarios

There have been many searches for SUSY particles from starting with LEP and still ongoing at the LHC today. As of yet there is no evidence for SUSY particles but there is still plenty of room to keep searching. The currently most stringent limits are in the gluino/squark sector because of large expected cross sections compared to gauginos/sleptons. These simplified models have been excluded up to X GeV masses. The most recent limits are shown in fig XYZ. The current best slepton and electroweak limits are shown in Figure ZYZ. Note that the electro weak limits are just reaching the TeV scale while SUSY remains valid at the few TeV level. Specifically the weakest limits are in the compressed regions for electroweakinos and sleptons.