Searching for new particles at the Large Hadron Collider

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Our current theory of the most fundamental laws of physics, known as the standard model (SM), works very well to explain many aspects of nature. Most recently, the Higgs boson, predicted to exist in the late 1960s, was discovered by the CMS and ATLAS collaborations at the Large Hadron Collider at CERN in 2012 [1] marking the first observation of the full spectrum of predicted SM particles. Despite the great success of this theory, there are several aspects of nature for which the SM description is completely lacking or unsatisfactory, including the identity of the astronomically observed dark matter and the mass of newly discovered Higgs boson. These and other apparent limitations of the SM motivate the search for new phenomena beyond the SM either directly at the LHC or indirectly with lower energy, high precision experiments.

In these proceedings, the successes and some of the shortcomings of the SM are described, followed by a description of the methods and status of the search for new phenomena at the LHC, with some focus on supersymmetry (SUSY) [2], a specific theory of physics beyond the standard model (BSM).

1 Standard model: successes and problems

The standard model of particle physics describes the interactions of fundamental matter particles (quarks and leptons) via the fundamental forces (mediated by the force carrying particles: the photon, gluon, and weak bosons). The Higgs boson, also a fundamental SM particle, plays a central role in the mechanism that determines the masses of the photon and weak bosons, as well as the rest of the standard model particles. In the early 20th century, the fundamental concepts of special relativity and quantum mechanics were developed. In the 1960s and 1970s, the standard model emerged as a combination of relativistic quantum field theories that describe the electroweak force, including the Higgs mechanism, and the strong force.

The SM has proven incredibly successful at describing many features of nature that we observe in our experiments. The most famous example, arguably, is the agreement of the SM prediction and the experimental measurement of the electron magnetic dipole moment to within 1 part per 100 billion [3]. The 2012 discovery of the Higgs boson was the culmination of almost fifty years of searching for the particle first predicted to exist in 1965 and first incorporated into the SM in 1967 with Glashow, Weinberg, and Salam's unification of the electromagnetic and weak forces. With the 2012 Higgs discovery, the full predicted particle spectrum of the SM was finally observed.

While these and other successes of the SM are a triumph for the field of particle physics, it is well known that the SM cannot be the ultimate theory of fundamental particles and interactions! Two of the most compelling shortcomings of the SM are its omission of the description of dark matter and its "fine tuned" description of the Higgs boson mass.

Dark matter was first postulated in the 1930s to explain Zwicky's observations that the behavior of the Coma Cluster constituents did not follow the Virial Theorem; established in the 1970s with Rubin and Ford's measurements that the rotational velocity of certain galaxies requires more matter than is visible; and finally described quantitatively through precise measurements of the Cosmic Microwave Background radiation, most recently by the Planck satellite. All evidence indicates that dark matter is a weakly interacting, potentially massive particle, for which there is no candidate in the SM. (The known neutrinos have already been ruled out as DM candidates.)

The “fine tuned” nature of the SM Higgs mass description arises from the quantum nature of the SM. In quantum mechanical theories, virtual particles are allowed to spontaneously come into existence and remain in existence for short periods of time. These virtual particles affect the measured properties of particles such as charge, magnetic moment, and mass. For example, we can think of the measured electron charge as the inextricable sum of the electron’s “bare” charge and the charge of the virtual particles near the electron. For most SM quantities, the bare contribution is dominant, and the virtual contribution is small. However, the story is different for the mass squared parameter of the Higgs potential in the SM (m_H^2). We can determine the value of m_H^2 from measurements of the Higgs boson mass, the W boson mass, and the strength of the weak force, and in doing so, we find that m_H^2 is relatively small: of the order 100 GeV. The virtual contribution to m_H^2 is very large in the SM, which means the bare contribution must also be very large and of opposite sign to cancel the virtual part and result in the small measured value for m_H^2. This exquisitely precise cancelation between two very large numbers to yield a single small number is known as “fine tuning.” Fine tuning has historically been the first sign that the cancelation is not coincidental, but instead, there is an additional unknown mechanism or symmetry that naturally requires the cancelation to occur.

2 Searching for new phenomena at the LHC

The LHC is a proton-proton (pp) collider that has been in operation since 2009 at a range of center-of-mass collision energies from 7 TeV to 13 TeV. In 2017, the LHC operated at 13 TeV with an instantaneous luminosity of 1.5×10^{34} cm^{-2} s^{-1}, which means it produced 1000 top quark pairs and 50 Higgs bosons per minute. At the LHC, we hope to directly produce and observe the dark matter particle or its relatives, and we also hope to understand the mechanism or symmetry that causes the apparently fine tuned cancelation in the Higgs theory described above.

Of the many theories proposed to address these two shortcomings of the SM, SUSY garners significant interest because it simultaneously explains both [4]. SUSY is a new spacetime symmetry relating bosons and fermions that causes their contributions to the Higgs potential to cancel nearly exactly. In addition to preventing divergence of the Higgs potential, a broad class of SUSY models naturally includes a DM candidate through the mechanism of R-parity (R_P) conservation. (Defined in terms of the baryon number B, lepton number L, and spin S as $R_P = (-1)^{3(B-L)+2s}$, R_P is even for SM particles and odd for SUSY particles.) In R_P conserving SUSY, the lightest SUSY particle is unable to decay and takes on the role of dark matter. Even more exciting is the principle of “naturalness” that implies that a few SUSY particles should have masses at the TeV scale for SUSY to prevent divergence of the Higgs potential [5]; that is, it would not be surprising or coincidental for SUSY particles to be produced at the LHC.

The first SUSY searches performed at a hadron collider are based on a few general and basic assumptions about the theory:

- Some SUSY particles will interact via the strong force, which means they will be produced with a high rate and they will produce jets of hadronic particles in their decays.
- In order to have avoided detection so far, SUSY particles will be relatively heavy, which means their decays will produce a large amount of energy in our detectors.
- The weakly interacting SUSY particle that is dark matter will neither decay, nor interact with our detectors. Thus, it will appear as “missing energy” when we reconstruct the entire collision.

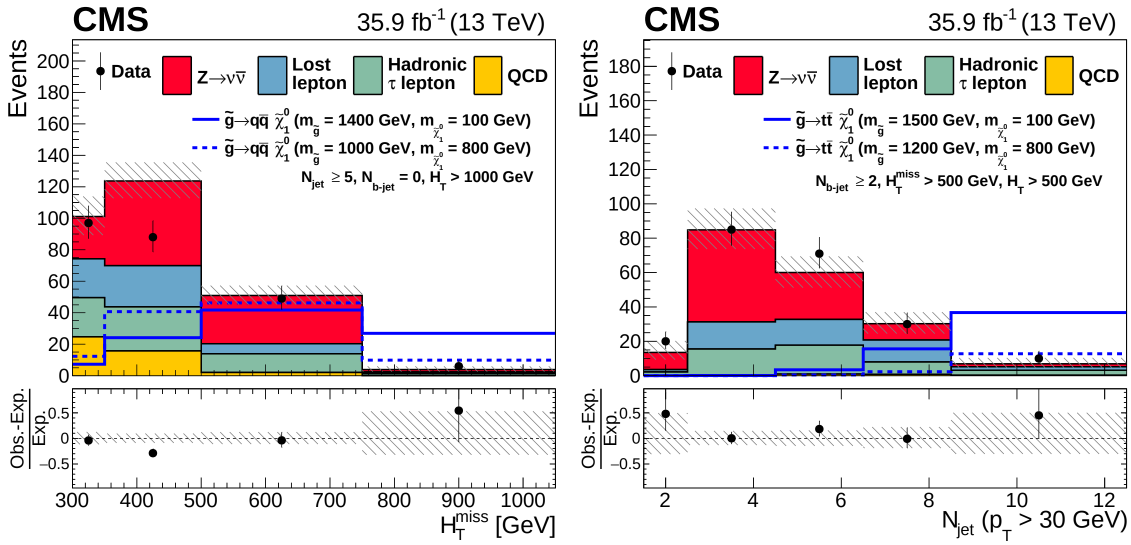

Figure 1: The observed numbers of events and SM background predictions for events particularly sensitive to gluino pair production followed by decay of each gluino to a neutralino and a pair of quarks. Distributions are shown as functions of missing energy $\mathrm{H}_{\mathrm{T}}^{\mathrm{miss}}$ (left) and jet multiplicity $\mathrm{N}_{\mathrm{jet}}$ (right). The event selection criteria are given in the figure legends. The hatched regions indicate the total uncertainties in the background predictions. The (unstacked) results for two example signal scenarios are shown in each instance for different values of gluino and neutralino masses.

Based on these simple assumptions, we sift through millions of pp collisions ("events") per second looking for potential SUSY events with large energy, many jets, and large missing energy. Of course, the SM also produces events with these properties, but relatively rarely. In our analysis of the LHC data, we use simulation and control samples in the data to determine how many SUSY-like events we expect from the SM. For example, one way that the SM can mimic SUSY events is through the production of Z bosons and several jets. The Z boson decays to a pair of neutrinos ($Z \to \nu\nu$) approximately 20% of the time. In such events, the undetected neutrinos result in significant missing energy in our event reconstruction, and the accompanying jets satisfy requirements for high jet multiplicity and large overall event energy. Fortunately, we can determine how many of these $Z \to \nu\nu$ events are expected in the SM because we know the relative rates for the Z boson to decay to neutrinos and charged leptons, and we can measure the number of events with Z bosons and many jets in which the Z boson decays to charged leptons. After performing similar estimates for each SM background, we would interpret a number of SUSY-like events in excess of our total SM prediction to be evidence of new phenomena.

So far, after collection of approximately 75 fb^{-1} of pp collisions at the LHC, CMS and ATLAS have discovered no evidence of new phenomena [6]. One specific CMS analysis, based on the variables described above, found no evidence of SUSY in 36 fb^{-1} of 13 TeV pp collisions collected in 2016 [7]. Figure 1 shows the observed numbers of events as functions of missing energy ($\mathrm{H}_{\mathrm{T}}^{\mathrm{miss}}$) and jet multiplicity ($\mathrm{N}_{\mathrm{jet}}$) for events with many jets, high event energy (H_{T}), and high missing energy in this analysis. Also shown are predictions for the SM and for specific models of SUSY. Despite SUSY expectations for events with large $\mathrm{H}_{\mathrm{T}}^{\mathrm{miss}}$ and $\mathrm{N}_{\mathrm{jet}}$, the observation is in good agreement with the SM prediction.

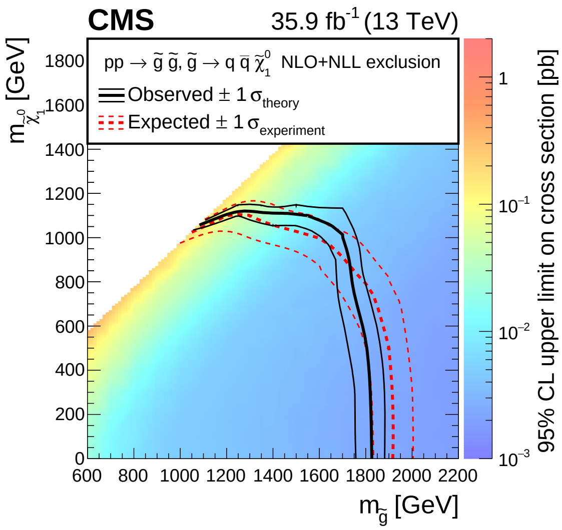

Figure 2: The 95% confidence level upper limits on the production cross section for gluino pair production followed by decay of each gluino to a neutralino and a pair of quarks, shown as function of the gluino and neutralino masses $m_{\tilde{g}}$ and $m_{\tilde{\chi}^0_1}$. The solid black curves show the observed exclusion contours with corresponding ± 1 standard deviation uncertainties. The dashed red curves show the expected limits with ± 1 standard deviation experimental uncertainties.

To use these null results to improve our understanding of experimentally allowed SUSY theories, we use simulations to understand what types of SUSY particles we would have been able to detect had these particles been produced and decayed in our detectors. The two properties of SUSY theories that most strongly effect our ability to produce and detect SUSY particles are the mass of the particles produced in the collisions, which is closely related to the rate of production, and the mass of undetected dark matter particles, which determines the amount of missing energy measured in the events. Figure 2 shows the values of masses of the produced SUSY particles that are not ruled out by the CMS analysis under the assumption that pairs of gluino SUSY particles are initially produced in the collision and then decay each into two quarks and a neutralino SUSY particle, which would be the DM particle. The horizontal axis shows the mass of the gluino particle, and the vertical axis shows the mass of the neutralino particle. The region to the lower left of the thick black line is excluded, and the region to the upper right is still allowed by the CMS data. For gluino masses above 2000 GeV, the production rate is so low what we would not have seen many SUSY particles in 36 fb^{-1} of 13 TeV pp collisions. For gluino masses around 1500 GeV and neutralino masses around 1200 GeV, the SUSY particles are produced, but are difficult to detect because the specific pattern of decays at these masses tends to result in low missing energy. In these events, the neutralinos carry most of the energy and exit the detector in a back-to-back fashion such that their missing energy cancels out, resulting in low total missing energy.

3 Conclusion and future prospects

Despite the incredible successes of the standard model of particles and interactions, we are nearly certain that it is not the ultimate description of nature at all energy scales. For this reason, one of the primary goals of the LHC is to discover new particles or phenomena that will allow us to start understanding the form of the eventual successor theory of the SM. So far, searches by CMS and ATLAS have given only null results allowing us to rule out strongly produced SUSY particles such as gluinos with masses up to approximately 2000 GeV.

In and around 2025, the LHC will undergo upgrades allowing instantaneous luminosities exceeding 5×10^{34} cm^{-2} s^{-1} and collection of an integrated luminosity exceeding 3 ab^{-1} into the mid 2030s. While the primary goal of this large dataset is to measure the properties of the Higgs boson as precisely as possible, we will also be able to extend the sensitivity to gluino pair production by about 1000 GeV. We will be able to probe the possibility of production of the most weakly produced SUSY particles. Even if the gluino is too heavy to be observed at the LHC, the naturalness principle mentioned above says that the weakly interacting higgsino particle could still be light enough to be produced at the LHC. Because it is so weakly produced, large datasets are required to observe the higgsino. Current limits on the higgsino mass come from the LEP experiments [8], which exclude masses below about 100 GeV. The full 3 ab^{-1} LHC dataset will allow both CMS and ATLAS separately to probe masses up to approximately 230 GeV.

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