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Prospects for SUSY and BSM Physics at the High Luminosity LHC

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Abstract. Prospects for the discovery of supersymmetry (SUSY) and other beyond-the-standard-model physics at the high-luminosity LHC are reviewed. Projections for the sensitivity for both strong and electroweak production of SUSY particles based on integrated luminosities up to 3000 fb^{-1} are presented, along with an analysis of several scenarios in which SUSY particles might be discovered. The potential complexity of the pattern of observed signals is highlighted, together with the importance of multi-signature "fingerprints," which can help to elucidate the origin of a signal. A brief discussion is also given for exotic particle searches, illustrating how high-luminosity data samples can provide key information on the properties of discovered particles.

MOTIVATIONS FOR NEW PHYSICS SEARCHES AT THE LHC

A central goal of the physics program of the Large Hadron Collider (LHC) is the exploration of particles and interactions at the TeV energy scale, which may hold answers to some of the most profound questions in particle physics. The mystery with the strongest empirical foundation is the nature of astrophysical dark matter. While there is no guarantee that the dark matter can be accounted for by weakly interacting massive particles (WIMPs) at the TeV scale, this explanation is well motivated, and the combined program of direct-detection experiments and further LHC searches are poised to make major progress in the next decade. A second, more theoretically motivated mystery, is the gauge hierarchy problem [1], which has become even more compelling with the discovery of the/a Higgs boson at a mass of approximately 125 GeV. Assuming that the Higgs is a fundamental scalar particle, its mass (and with it the entire electroweak scale) is subject to enormous short-distance quantum corrections which, on their own, would pull its value to some high cutoff scale, such as the Planck scale. This uncomfortable outcome can be avoided either by extreme fine tuning of the bare Higgs mass parameter, which is regarded as (extremely) unnatural, or by some new physics that cancels the effects of the quantum corrections. It is remarkable that this acute problem can be addressed by new physics scenarios ranging from supersymmetry (SUSY) to extra dimensions. Regardless of the physical mechanism, the new physics is expected to emerge somewhere around the TeV scale if fine tuning is to be avoided. A third mystery is whether the three standard model (SM) gauge coupling constants evolve with increasing energy such that they unify at some high scale, where a unified gauge group with this single gauge coupling constant would govern all non-gravitational interactions. The presence of SUSY at the TeV scale can lead to convergence of the running coupling constants at a high scale. Of course, a key element of the High Luminosity (HL) LHC program is the fullest possible study of the Higgs sector, which is covered in a separate talk by Aleandro Nisati at this conference. Thus, there are many indications, but no guarantees, that exploration of the TeV scale will lead to the discovery of new physics beyond the SM.

This talk considers the long-term discovery potential of the ATLAS [2] and CMS [3] experiments at LHC and High Luminosity (HL) LHC physics programs, which should help to resolve these mysteries and many others. Because of time constaints, I will focus on supersymmetry, but studies of other ("exotic") beyond-the-standard-model (BSM) scenarios are discussed briefly as well.

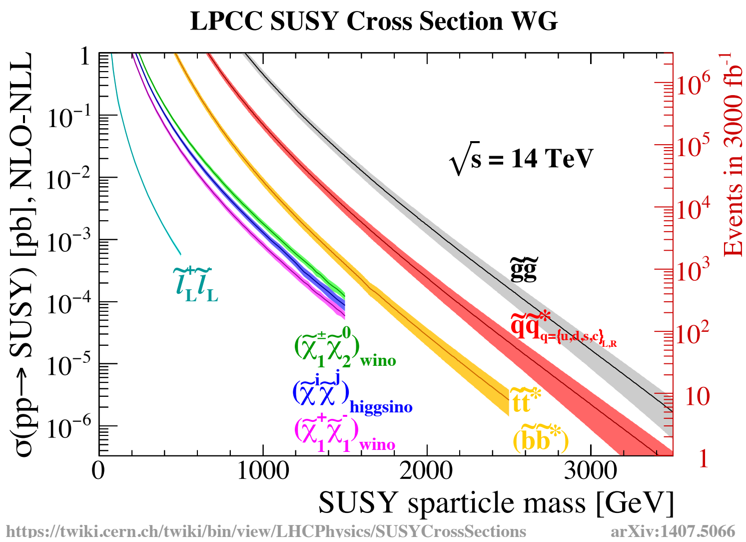

FIGURE 1. Cross sections for the pair production of supersymmetric particles at $\sqrt{s}$ = 14 TeV, as a function of the SUSY particle mass [4]. The number of produced events in a sample of 3000 fb^{-1} is also given.

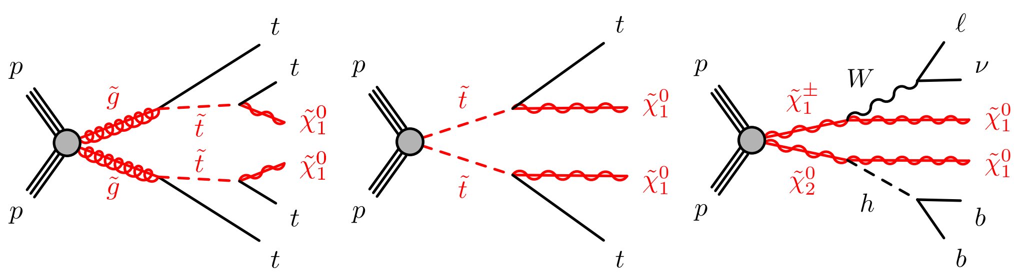

FIGURE 2. Diagrams for SUSY particle pair production and decay in the context of simplified models: (left) gluino pair production with decay into a top squark and an (anti-) top quark, (middle) top-squark + anti-top squark pair production, and (right) production of a chargino-neutralino pair.

SUSY SEARCHES: A SHORT PRIMER AND STATUS OF CURRENT SEARCHES

To understand the program of SUSY searches, it is useful to start from the cross sections for the most important processes. Figure 1 shows the dependence of key pair-production cross sections (left-hand axis) on the mass of the pair-produced SUSY particle in pp collisions at $\sqrt{s}$ = 14 TeV [4]. The cross sections fall off rapidly with mass, as one would expect. At fixed particle mass, the largest cross section is for gluino pair production ($\tilde{g}\tilde{g}$). For example, for $m(\tilde{g})$ = 2 TeV, the cross section would be around 1 fb, yielding several thousands of produced events (right-hand axis) in the expected nominal HL-LHC sample of 3000 fb^{-1}. The pair production cross section for a specific scalar quark (squark) is much smaller, as shown for $\tilde{t}\tilde{t}^*$. (Here, an asterisk is used to denote an antiparticle rather than an off-shell particle.) Searches for top-squark pair production must therefore contend with a small cross section, as well as with a large SM background from $t\bar{t}$ production. As shown in Fig. 1, the combined cross section for squark-antisquark production, integrating over all squark degrees of freedom in the first two generations (two scalar partners, L and R, for each SM fermion, times four flavors), gives eight times this basic squark-antisquark cross section. Thus, under the assumption of degenerate squark masses, such searches generally have a much larger mass reach than a search for $\tilde{t}\tilde{t}^*$ alone. As we will see, however, a characteristic of natural SUSY scenarios is that, while both top squarks and one of the bottom squarks are typically constrained to be light, no such constraint applies to the first and second generation squarks. Figure 1 also shows that the cross sections for electroweak processes are much smaller at fixed mass than any of the strong production processes.

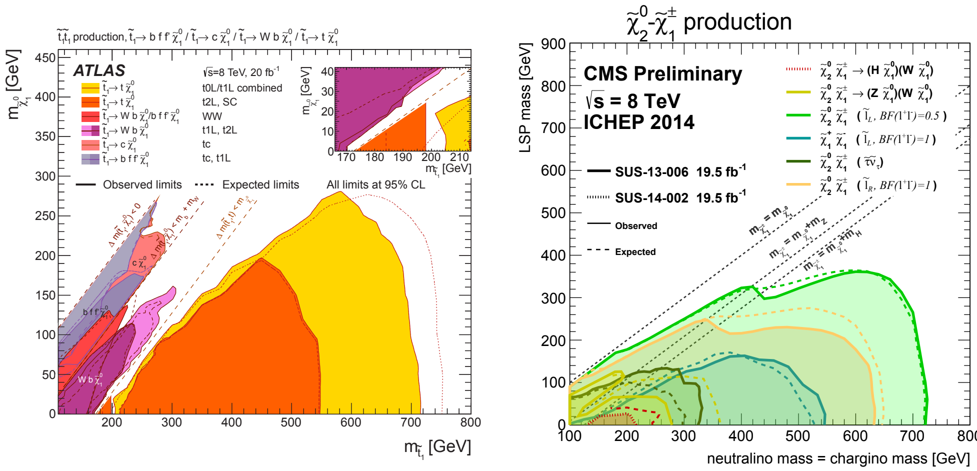

FIGURE 3. (Left) Summary of ATLAS searches for top-squark pair production: excluded regions in the $m(\tilde{t})$-$m(\tilde{\chi}_1^0)$ plane using Run 1 data [6]. (Right) Summary of CMS searches for EWKino pair production using Run 1 data [7].

To define a signal hypothesis, production processes such as those shown in Fig. 1 must be combined with a set of specified decay modes, which depend on the assumed mass spectrum of lighter SUSY particles, and potentially on mixing angles as well. Many of the exclusion plots are presented in the framework of simplified model spectra (SMS) [5], in which it is assumed that a very limited number of SUSY partners are involved in the decay chains of the produced particles. Under the assumption that the combined product branching fraction for the specified process is 100%, the excluded cross section is compared to a theoretical cross section, yielding an interpretation in terms of excluded SUSY particle masses. This approach greatly simplifies the interpretation, at the likely expense of some realism. Such models are used in many, but not all, ATLAS and CMS studies of sensitivity at the HL-LHC. Figure 2 shows a representative set of the many simplified models that have been defined for use in the design and interpretation of SUSY searches. In a full-spectrum SUSY model, the branching fraction for a given mode would typically be lower than the 100% value assumed in an simplified model, with a corresponding degradation in the mass reach of the search.

Figure 3 shows the exclusion regions resulting from the ATLAS Run 1 searches for top-squark pair production [6]. The regions are defined in the parameter space of a set of simplified models in which the only relevant SUSY particles are the lighter top squark ($\tilde{t}_1$) and the neutralino LSP ($\tilde{\chi}_1^0$). Depending on the masses of the $\tilde{t}_1$ and the χ_1^0, a variety of different two-, three-, and four-body decay scenarios can occur, and limits are placed on each one assuming a 100% branching fraction. The most basic two-body decay is $\tilde{t}_1 \to t\tilde{\chi}_1^0$; if there is not sufficient phase space for the top quark to be produced, the process becomes $\tilde{t}_1 \to bW^+\tilde{\chi}_1^0$, as long as the W-boson can be produced on mass shell. Roughly speaking, top squarks with masses up to $m(\tilde{t}) \approx 725$ GeV have been excluded for low values of $m(\tilde{\chi}_1^0)$. For $m(\tilde{\chi}_1^0) \geq 275$ GeV, however, there is no constraint on $m(\tilde{t}_1)$. In such exclusion plots, the mass of the produced particle is shown on the x-axis, so the decrease in cross section with increasing mass will always cut off the exluded region in this direction. The neutralino (LSP) mass is plotted on the y-axis; as its value approaches that of the top-squark mass, the amount of missing transverse energy, $E_T^{\text{miss}} = |\vec{p}_T^{\text{miss}}|$, in an event is reduced, and the detection efficiency falls off correspondingly. Figure 3 (right) shows the exclusion regions from CMS Run 1 searches for the pair production of neutralinos and/or charginos in a variety of simplified models [7]. Such particles are referred to generically as "electroweakinos" (EWKinos).

Naturalness considerations arising from the gauge hierachy problem constrain only a subset of the SUSY particles [8]. These are $\tilde{t}_L$ and $\tilde{t}_R$ (or the mass eigenstates $\tilde{t}_1$ and $\tilde{t}_2$), $\tilde{b}_L$, $\tilde{g}$, and the Higgsinos, denoted by $\tilde{H}$. Other SUSY particles are not generically constrained to be light and are typically assumed to be heavy and decoupled from the physics. As a consquence, the minimal natural SUSY spectrum has relatively few particles, and such models are typically handled reasonably well in simplified-model frameworks, in which there are only 2–3 particles. Although "natural SUSY endures" [8] is still the dominant fashion, this paradigm is under considerable stress from Run 1 results [9]. In any case, while natural SUSY is a key focus of investigations, CMS and ATLAS searches are not limited to these scenarios.

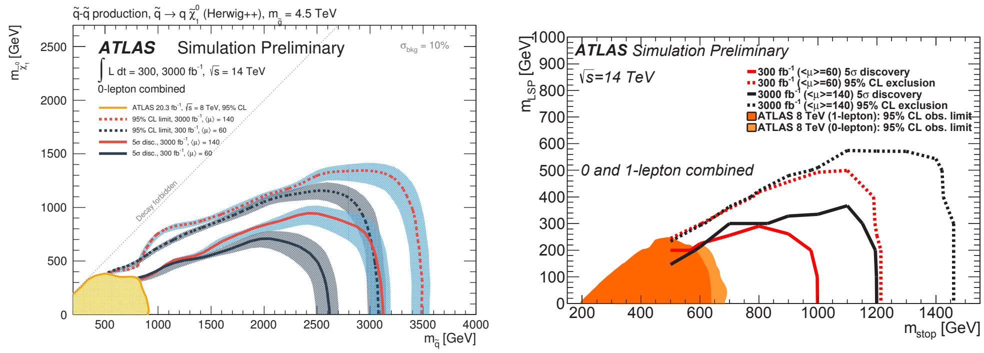

FIGURE 4. ATLAS estimates of the expected sensitivity to (left) squark-antisquark production (summed over eight states) [10] and (right) top squark + anti-top squark production [11] for samples with 300 fb^{-1} and 3000 fb^{-1}.

SUSY DISCOVERY REACH PROJECTIONS

In this section we consider ATLAS and CMS estimates of the sensitivity of future searches to SUSY particles with data samples from 300 fb^{-1} to 3000 fb^{-1}. Most of these studies use simulated event samples with parametrized detector performance descriptions and with background uncertainties that are either guessed (motivated by similar searches with 8 TeV data) or simply assumed. The searches usually employ very tight event selection criteria and operate on the extreme tails of the kinematic distributions of the SM backgrounds. In most but not all cases, the studies use simple, non-optimized methods, and it is best to regard the results as indicative and not to take them too literally.

We start with strong production processes. Figure 4 (left) shows the expected ATLAS sensitivity [10] from a search in the zero-lepton channel for squark pair production with the decay $\tilde{q} \to q\tilde{\chi}_1^0$, summing over cross sections for eight mass-degenerate squarks from the first and second generations. The event selection requires no leptons, 2–6 jets, large $E_T^{\rm miss}$, and large $m_{\rm eff}$ (the sum of transverse momenta of the jets plus $E_T^{\rm miss}$). With a sample of 3000 fb^{-1}, degenerate squarks with masses up to 3.1 TeV can be discovered at 5σ significance; squarks with masses up to 3.5 TeV can be excluded at 95% CL. Figure 4 (right) shows the estimated ATLAS sensitivity [11] from a simulated search for top-squark pair production. Here, two separate event selections are used, one requiring no leptons, ≥ 6 jets, ≥ 2 *b*-tagged jets, and large $E_T^{\rm miss}$ and the other requiring 1 lepton, ≥ 4 jets, ≥ 1 *b*-tagged jet, and large $E_T^{\rm miss}$. Top squarks with masses up to 1.2 TeV can be discovered at 5σ significance; the 95% CL exclusion curve excludes masses up to roughly 1.4 TeV. The results from the zero-lepton and one-lepton search channels have been combined.

Figure 5 shows the expected sensitivity of CMS and ATLAS to the pair production of EWKinos. The production of $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$, with $\tilde{\chi}_1^\pm \to W^\pm\chi_1^0$ and $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$, can be probed in a search for $Wh(bb) + E_T^{\rm miss}$. Here, the signature includes a single lepton, a pair of *b*-tagged reconstructing to the Higgs-boson mass, and other kinematic variables such as $E_T^{\rm miss}$. In a study based on full simulation, CMS [12] finds that, with 3000 fb^{-1}, the 5σ discovery sensitivity extends up to $m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_2^0) \approx 950$ GeV, where the masses of the produced chargino and neutralino are assumed to be equal for simplicity. The EWKino discovery reach is much larger than what would be obtained with only 300 fb^{-1}, where

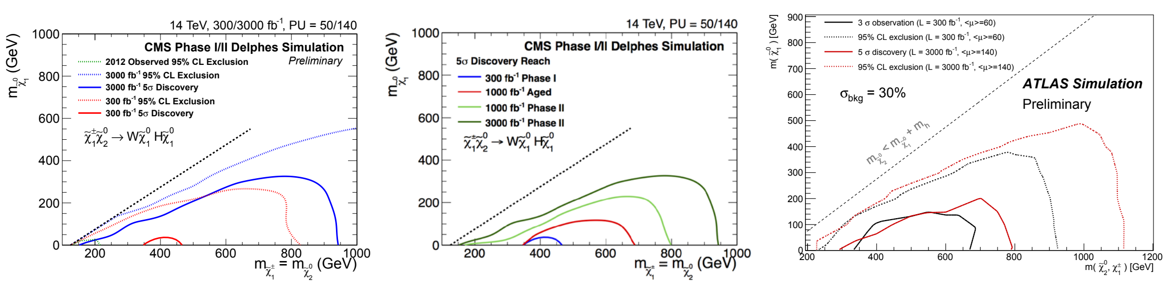

FIGURE 5. Estimated sensitivity to chargino-neutralino pair production from CMS [12] (left, middle) and ATLAS [13] (right).

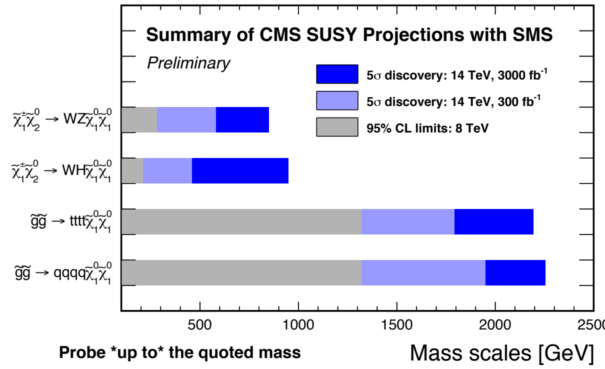

FIGURE 6. Summary of CMS SUSY mass reach projections [12] for integrated luminosities of 300 fb^{-1} and 3000 fb^{-1}. Results are given for simplified models involving EWKino pair production and gluino pair production.

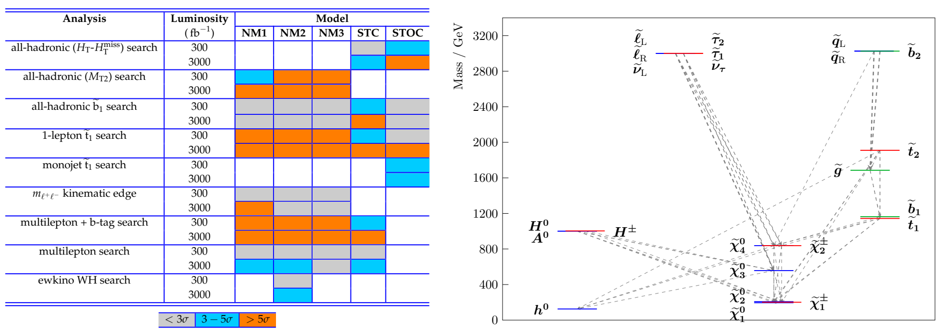

FIGURE 7. (Left) Summary of CMS study [12] of discovery scenarios in full-spectrum SUSY models. The color code indicates whether the observed significance would be $< 3\sigma$ (grey), $3 - 5\sigma$ (blue), or $> 5\sigma$ (orange) and is given for both 300 fb^{-1} and 3000 fb^{-1}. (Right) Mass spectrum for the NM3 model.

there is barely any reach at all. This situation is characteristic of electroweak (low cross section) production processes. Figure 5 (middle) shows the results of a related CMS study designed to assess the impact of using an aged detector through 1000^{-1} fb, as compared to an upgraded detector. It is clear that there are major gains in this search associated with the upgraded detector. Figure 5 (right) shows similar results from ATLAS [13]. The discovery reach of 800 GeV corresponds to a cut and count analysis; using a multivariate discriminator, the sensitivity is extended to 950 GeV. If $\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0$ instead of $h\tilde{\chi}_1^0$, the search is performed in the trilepton channel. ATLAS obtains [10] 5σ discovery sensitivity up to $m(\tilde{\chi}_1^{\pm}) = m(\tilde{\chi}_2^0) = 820$ GeV, assuming that the initial EWKinos are Winos.

Figure 6 summarizes the mass reach of CMS in several channels involving gluino pair production and EWKino pair production [12]. The discovery sensitivity for gluinos extends up to about 2.2 TeV with 3000 fb^{-1} and for neutralino/chargino pairs discovery sensitivity extends to about 1 TeV. The upper value of the mass shown corresponds to the reach achieved at low LSP mass. The largest relative increase in sensitivity with the 3000 fb^{-1} data sample is for the direct production of electroweak SUSY partners, because of their small production cross section. CMS finds that there is up to 500 GeV increase in discovery reach with the HL-LHC for chargino-neutralino production studied in the $Wh(bb) + p_T^{\rm miss}$ final state. Thus, if strongly interacting SUSY partners are too heavy to be produced, EWKinos, which could be lighter, may still provide a window to SUSY at the HL-LHC.

DISCOVERY SCENARIOS WITH FULL-SPECTRUM SUSY MODELS

The observation of a significant excess event yield over the SM background contributions in a particular search channel would be tremendously exciting. The simplified model framework can be misleading, however, because the (very) naive expectation is that an excess observed in a search for a particular process implies that the targeted process itself has been observed. This conlusion is, of course, not correct: an excess in a given search channel can arise from many different physics processes because typical SUSY search signatures are inclusive. To investigate the issue of how patterns of signals in different channels might be used to understand the origin of such excess event yields, CMS has studied [12] five full-spectrum SUSY models, performing analyses on nine separate signatures in parallel. The models are designated NM1, NM2, NM3 (natural models), STC (stau co-annihilation model), and STOC (stop co-annihilation model). For NM1-3, $m(\tilde{g}) = 1.7$ TeV and $m(\tilde{t}_1) = 1.1$ TeV. The branching fraction $B(\tilde{t} \to t\tilde{\chi}_1^0)$ is 0.6%, 1.5%, and 39%, respectively, in these models, due to differences in their electoweak sectors. In STC, $m(\tilde{\tau}_1) \approx m(\tilde{\chi}_1^0) \approx 190$ GeV, and in STOC, $m(\tilde{t}_1) \approx m(\tilde{\chi}_1^0) \approx 400$ GeV. A full description of each model is given in the references. NM1 includes the decay $\tilde{\chi}_2^0 \to \tilde{\ell}^\pm \ell^\mp \to \ell^+\ell^-\tilde{\chi}_1^0$, which generates the famous dilepton "edge" signature in the dilepton mass spectrum. In NM2, $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production leads to a signature in the $Wh(bb) + E_{\mathrm{T}}^{\mathrm{miss}}$ final state. The STOC model is quite distinctive in that $\tilde{t}_1 \to c\tilde{\chi}_1^0$ proceeds with a branching fraction of nearly 100% because of the small mass splitting.

Figure 7 (left) shows, in color-coded form, the expected significance for each of the different experimental signatures investigated, while Fig. 7 (right) shows the mass spectrum for NM3. The patterns of significances show that very different amounts of data are required to obtain the full "fingerprint" of a given model. Furthermore, partly because there are no mass peaks in the SUSY signatures, the interpretation of even a full pattern of excess event yields is a complex matter. Thus, the discovery of a SUSY-related excess could well be very different from that for the Higgs boson, where the interpretation came very rapidly. Here, a discovery could involve multiple 3-4 σ excesses, rather than a single 5σ excess, and confirmation and interpretation could require many years of investigation at the HL-LHC.

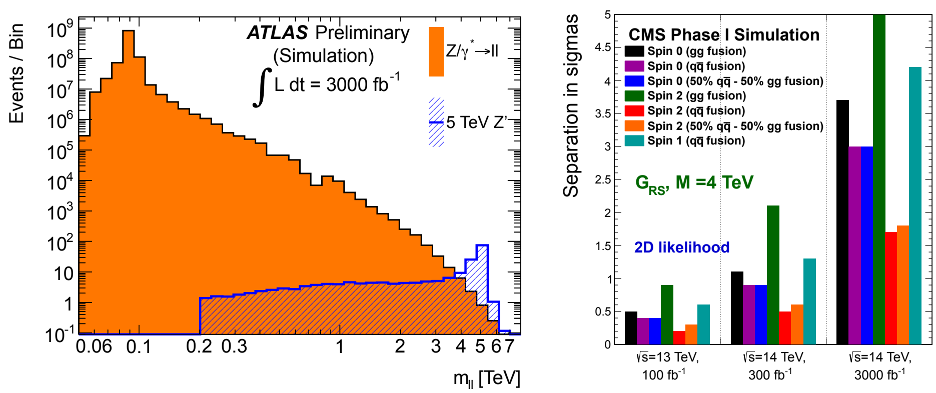

FIGURE 8. Studies of sensitivity to dilepton resonances in simulated event samples: (left) ATLAS study [16] of a sequential-standard-model (SSM) Z' boson and (right) CMS study [18] of spin determination for a Randall-Sundrum ($J = 2$) graviton.

EXOTIC PARTICLE SEARCHES

ATLAS and CMS have performed a broad range of studies to assess the discovery reach with high luminosity samples and to undertand the impact of detector performance on exotica searches. The areas investigated include dilepton and di-top resonances, dark matter, R-parity violating and stealth SUSY, degenerate Higgsinos, heavy stable charged particles, long-lived particles with displaced vertices, and more [14, 15, 16, 17]. Here we briefly consider dilepton resonance searches, which are sensitive to a variety of BSM scenarios. Figure 8 (left) shows the distribution of $m(\ell^+\ell^-)$ from ATLAS [16] for a simulated dilepton resonance search with 3000 fb^{-1}. One can exclude (95% CL) a sequential standard model Z boson (Z'_{SSM}), which has the same couplings at the SM Z boson, up to a mass of around 8 TeV. While this coupling scenario is not considered to be a highly motivated physics scenario, it is a standard physics benchmark. Figure 8 (right) shows the results of a CMS study [18] of how well one can determine the spin of such a resonance, assuming that its mass is 4 TeV. At this mass, one would obtain a few events with 100 fb^{-1} and 100-400 events with 3000 fb^{-1}. The figure shows the separation (in units of σ) between the true hypothesis, in this case a $J = 2$ Randall-Sundrum graviton, and a variety of other spin 0, 1, and 2 hypotheses. It is clear that the HL-LHC data sample provides extremely valuable information in this study.

CONCLUSIONS

Just as Columbus first "discovered" America by finding several islands in the Caribbean Sea, the observation of the top quark, and the W, Z, and Higgs bosons may just be the first sightings at the TeV scale. Full exploration of this scale will likely require a broad, multi-decade physics program.

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