Search for beyond the standard model physics at the LHC

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Both CMS and ATLAS collaborations have performed searches for physics beyond the standard model of particle physics in a variety of final states using the proton-proton collision data collected during the LHC Run 1 at the center-of-mass energy of $\sqrt{s}$ = 7–8 TeV. In this paper, a review of recent results from these searches are presented. Future prospects for these searches from the LHC experiments are also discussed.

1 Introduction

The Run 1 operation of the Large Hadron Collider (LHC) from 2009 to 2012 was extremely successful. The long-sought Higgs boson was discovered by the CMS and ATLAS collaborations, which completed the standard model (SM). However, there are still many open questions in particle physics, such as the gauge hierarchy problem and the identify of dark matter, and the standard model is often considered as a low-energy approximation of a more complete theory. Both CMS and ATLAS have performed a variety of new physics searches using the Run 1 data, and more than 100 results based on the 2012 data of 8 TeV proton-proton collisions are made public [1, 2]. In this conference proceedings, I will present only some highlights of these results.

2 Search for resonances

Mass resonances are simple yet powerful probes to discover new particles, and new particles that will produce mass resonance signatures are predicted in many beyond-the-standard-model (BSM) scenarios. Single mass resonances are predicted by, e.g., extended gauge theories [W'/Z'], compositeness [excited fermions], Randall-Sundrum (RS) model [Kaluza-Klein gravitons/gluons], and paired mass resonances may be produced by, e.g., gluinos/squarks in the case of supersymmetry, and also by leptoquarks, vector-like quarks, and colorons. Searches for new physics in dilepton mass spectra were performed by both CMS [3] and ATLAS [4]. The m_{ee} spectrum measured by ATLAS is shown in Fig. 1(a). No resonant structure is observed and Z's with the SM Z couplings are excluded up to 2.9 TeV [3, 4].

The forward-backward asymmetry of dielectron pairs in the same dataset, $A_{\mathrm{FB}} = (N_{\mathrm{F}} - N_{\mathrm{B}})/(N_{\mathrm{F}} + N_{\mathrm{B}})$ where N_F (N_B) is the number of events with $\cos\theta^* > 0$ ($\cos\theta^* < 0$) and θ^* is the dielectron decay angle, provides extra handles to search for non-resonant new physics signatures originating from contact interactions or large extra spatial dimensions. No significant deviations from the SM background expectations are observed as shown in Fig. 1(b) and lower limits are set on the contact interaction scale Λ up to 26 TeV [5].

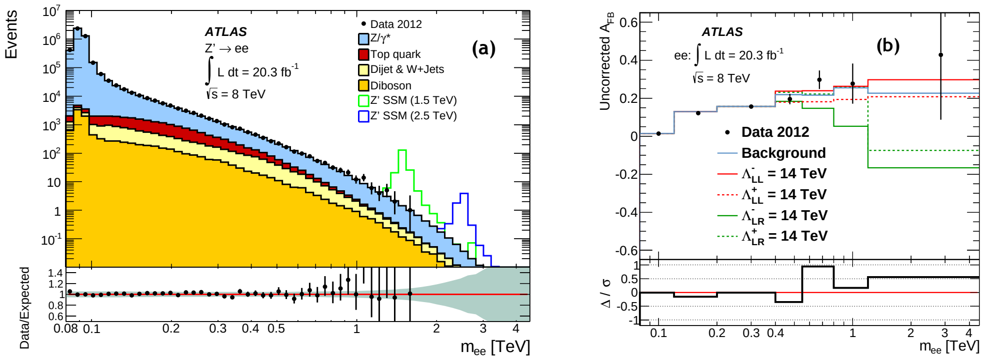

Figure 1: (a) The $m_{\rm ee}$ distributions with two selected Z' signals overlaid, compared to the stacked sum of all expected backgrounds, and the ratios of data to the background expectation [4]. (b) Reconstructed $A_{\rm FB}$ distributions for data and the SM background estimation versus $m_{\rm ee}$ together with the predictions of different Λ values for the contact interaction model [5].

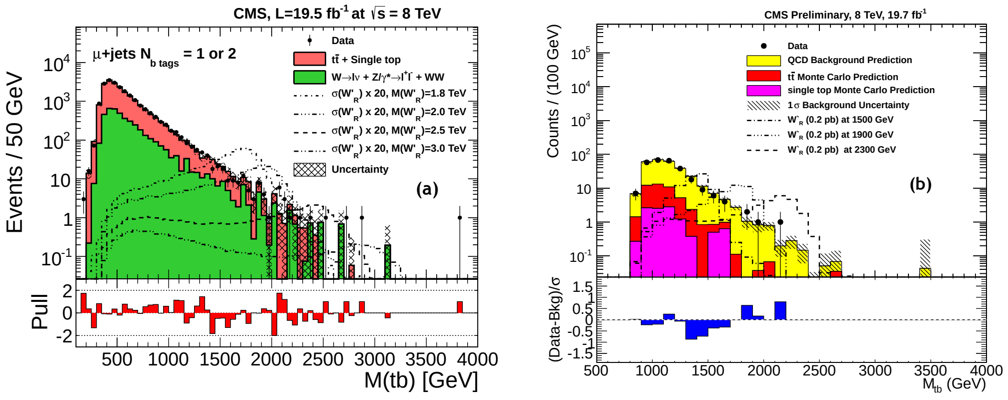

Figure 2: The $m_{\rm tb}$ distributions in the (a) semi-leptonic [6] and (b) all-hadronic [7] channel together with simulated W' signal distributions.

Searches for W's decaying to the top-bottom quark pairs have been performed by both CMS [6, 7] and ATLAS [8, 9]. The $m_{\rm tb}$ mass spectra measured in the semi-leptonic ($\rm W' \to tb, t \to Wb \to (l\nu)b$) and all-hadronic ($\rm W' \to tb, t \to Wb \to (q\bar{q}')b$) channels by CMS are shown in Fig. 2. The right-handed W' is excluded up to about 2 TeV. For the all-hadronic searches [7, 9], the jet substructure technique is used to identify hadronically-decaying boosted top quarks from W' decays. New physics searches at the LHC often involve high-$p_{\rm T}$ boosted top/W's, and jet substructure tools based on "fat" jets with the size parameters $R = 0.8$–1.5 are widely used.

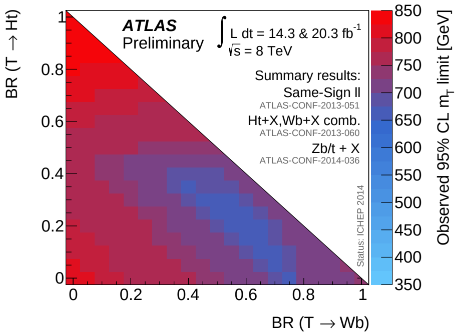

Figure 3: Observed lower limits on the mass of vector-like T quarks from ATLAS searches in the branching-ratio plane.

New heavy vector-like quarks emerge as a characteristic feature of some BSM models, including extra dimensions and composite Higgs models. They have been extensively searched for by CMS [10, 11] and ATLAS [12, 13, 14]. A new charge +2/3 quark, T, undergo three decay modes: T → Zt, Ht, and Wb. Searches have been performed in different channels to cover various branching fraction hypotheses. Searches in the opposite-sign dileptons and $\geq$ 3 leptons + b-tags channels are sensitive to the T → Zt decay [12]. A search with boosted W + b-tags [13] provides sensitivities to T → Wb, and a search with the same-sign dileptons + b-tags [14] is sensitive to T → Zt and T → Ht. As shown in Fig. 3, these complementary searches provide sensitivities to a wide range of branching fractions. The current lower bounds on the T mass are about 690–780 GeV from CMS [10] and 550–850 GeV from ATLAS [12, 13, 14].

3 Search for dark matter

Currently one of the most important questions in particle physics is the identify of dark matter (DM). There are strong indications from many astronomical observations that there are DM particles which do not interact via strong or electromagnetic forces and are heavy enough so that they move slowly compared to the speed of light; however, such particles have not been observed in the laboratory yet. Many ground-based experiments looking for DM-nucleon scattering (direct searches) and experiments in space looking for signals from DM annihilation or decays (indirect searches) have been built. At the LHC, DM particles may be pair-produced in proton-proton collisions either directly or through cascade decays of heavier new particles. The DM particles do not interact with the CMS and ATLAS detectors; however, they can still be observed when they are boosted against initial state radiation of gluons, quarks, vector-bosons, and photons. If these radiated particles have high p_{T}, they result in the final state of mono-“X” and large missing E_{T}. Since particles that mediate interactions between SM particles and DM particles are not known, the effective field theory (EFT) is often used to model these interactions as contact interactions in interpretation of LHC DM search results. This is considered as a good model for heavy mediator masses (> 3 TeV); however, a special care is necessary for lighter mediators.

CMS and ATLAS have searched for DM particles in mono-jet [15], mono-photon [16], mono-W/Z [17, 18, 19, 20], mono-top [21, 22], and di-top [23] final states associated with large missing E_T in the 8 TeV data. The mono-jet search results from CMS are shown in Fig 4(a). Searches in different final states provide the information about couplings of mediator particles to different flavors of quarks and gluons. Limits are set on the EFT contact interaction scale Λ using effective operators, and they are further translated to limits on elastic DM-nucleon cross section as a function of DM particle mass as shown in Fig. 4(b). Compared to results from direct dark matter searches, LHC results are more independent of DM masses up to kinematic limits of a few hundred GeV, more stringent at low DM masses, and less sensitive to the spin-dependence of the couplings.

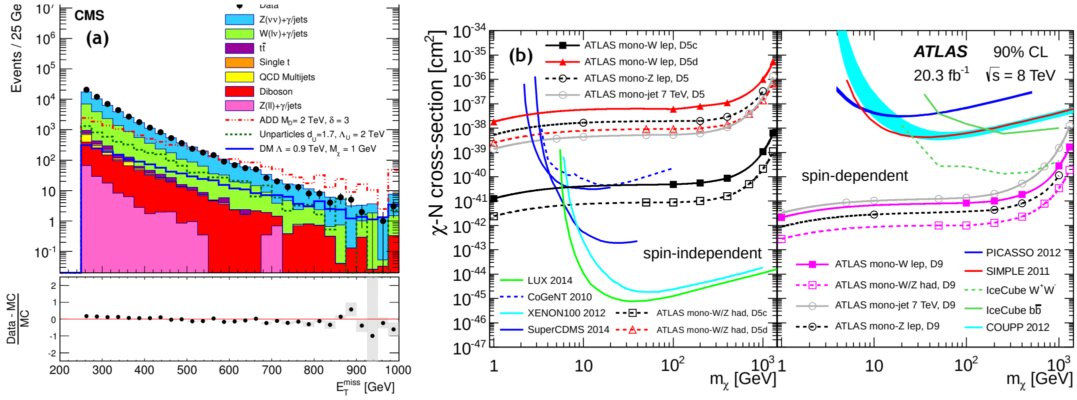

Figure 4: (a) Missing $E_{\rm T}$ distributions from the mono-jet search [15]. (b) The upper limits on the DM-nucleon cross section as a function of DM particle mass from searches in the mono-jet, mono-W, and mono-Z channels [19] for the spin-independent and spin-dependent EFT operators, together with limits from other experiments.

Some class of BSM models, called Higgs portal DM models, predict that a DM particle ($\tilde{\chi}$) interacts with SM particles only through the Higgs exchange process and the Higgs decays in the $\mathrm{H} \to \tilde{\chi}\tilde{\chi}$ mode. CMS searched for this signature in the vector boson fusion (VBF) channel and the $\mathrm{Z}(\to \ell\ell, \mathrm{b\bar{b}}) + \mathrm{H}$ channel [24]. The limit was placed on $\mathrm{Br}(\mathrm{H} \to \tilde{\chi}\tilde{\chi}) < 0.68$ (0.81) from the VBF (ZH) channel search, and the results are also presented in terms of the DM-nucleon cross section as shown in Fig. 5.

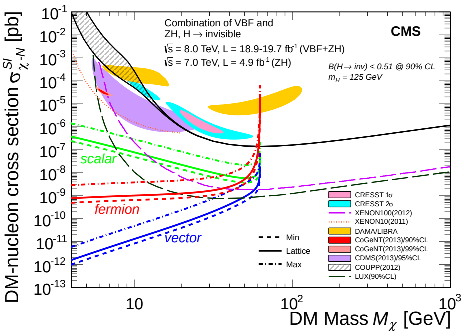

Figure 5: The upper limits on the DM-nucleon cross section versus DM particle mass from the $\mathrm{H} \to \tilde{\chi}\tilde{\chi}$ searches [24].

4 Search for supersymmetry

Supersymmetry (SUSY) is a well motivated BSM theory. In SUSY, the lightest supersymmetric particle (LSP) is considered a valid DM candidate. A broad class of SUSY scenarios with light third generation squarks and gluiness, known as natural models, can address the gauge hierarchy problem.

An extensive program to search for SUSY was carried out by CMS and ATLAS. Searches in the jets + missing $E_{\rm T}$ final state provide sensitivities to a wide class of SUSY models [25, 26]. Search results from ATLAS in this channel [25] are shown in Fig. 6(a). Mass exclusions reach up to about 1.4 TeV for gluinos ($\tilde{\mathrm{g}}$) and 0.9 TeV for the first- and second-generation squarks ($\tilde{\mathrm{q}}$). The inclusive searches with b-tags test natural SUSY models with TeV-scale gluinos, lighter top and bottom squarks, and nearly mass-degenerate charginos/neutralinos [27, 28]. Results from CMS [27] are shown in Fig. 6(b) for models with various gluino decay modes. The sensitivities generally degrade when there are more top quarks in the final state due to complex top quark decays.

The top squark ($\tilde{\mathrm{t}}_1$) is extensively searched for by CMS [29, 30, 31] and ATLAS [32, 33, 34, 35]

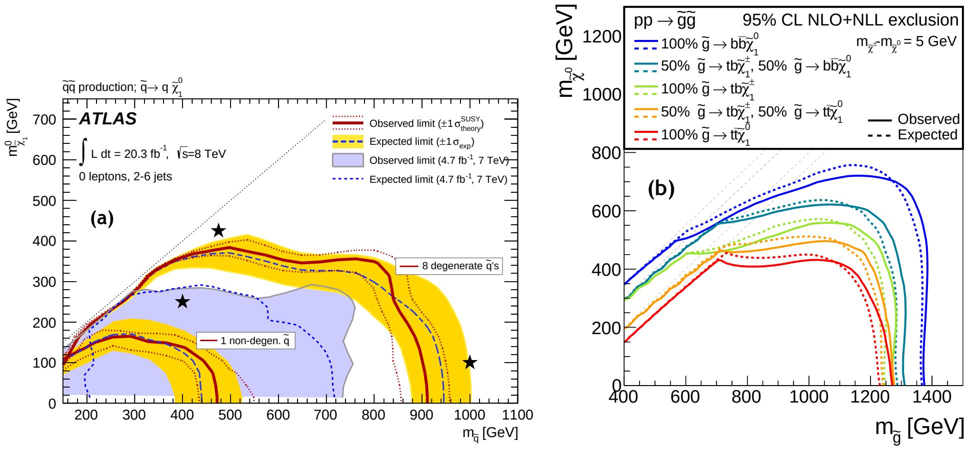

Figure 6: (a) Squark mass limits in the $m_{\tilde{q}}$-$m_{\tilde{\chi}_1^0}$ plane [25], and (b) gluino mass limits in the $m_{\tilde{g}}$-$m_{\tilde{\chi}_1^0}$ plane obtained for different gluino branching fraction models [27].

given its important role for addressing the gauge hierarchy problem. The dominant decay channel of the top squark varies over different SUSY scenarios and largely depends on available phase space for each decay mode. Results of complementary searches by ATLAS in different final states targeting different top squark decay modes are summarized in Fig. 7(a). The $\tilde{t}_1 \to t\tilde{\chi}_1^0$ decay mode is searched for in the 0-, 1-, and 2-lepton final states [32, 33, 34], and the mass exclusion extends up to about 700 GeV in the top squark mass. If $m_b + m_W + m_{\tilde{\chi}_1^0} < m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$, the top squark often decays through $\tilde{t}_1 \to Wb\tilde{\chi}_1^0$, and searches in the 1- and 2-lepton channels provide sensitivities. If $m_{\tilde{t}_1} < m_b + m_W + m_{\tilde{\chi}_1^0}$, the top squark often decays through

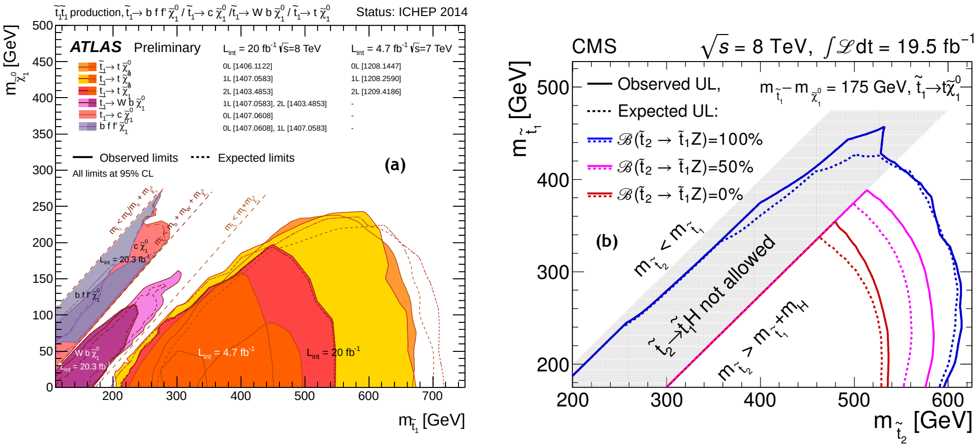

Figure 7: (a) Exclusion limits for top squark pair production from ATLAS [32, 33, 34, 35] shown in the $m_{\tilde{t}_1}$-$m_{\tilde{\chi}_1^0}$ plane. (b) Exclusion limits for $\tilde{t}_2$-pair production for different branching fractions of $\tilde{t}_2 \to Z(H)\tilde{t}_1$ [37].

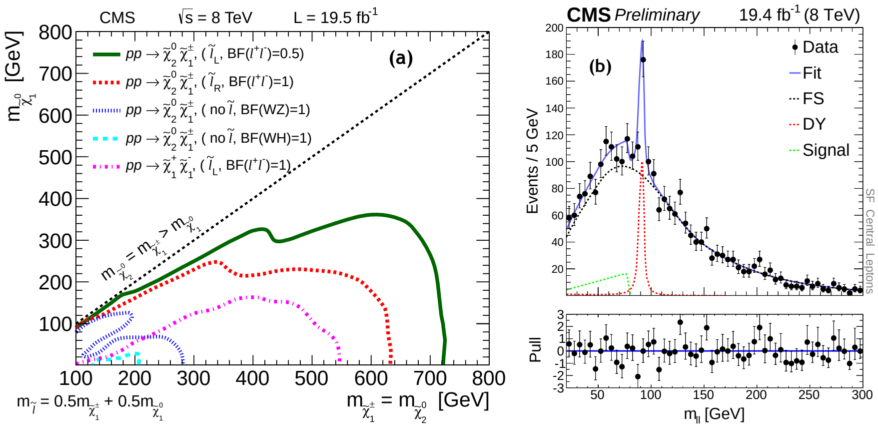

Figure 8: (a) Mass exclusions for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production with different decays, and for $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production [38]. (b) Measured dilepton mass distributions with fits with the signal + background hypothesis in a dilepton mass spectrum endpoint search [44].

$\tilde{t}_1 \to c\tilde{\chi}_1^0$ or $\tilde{t}_1 \to bff'\tilde{\chi}_1^0$. In the case of $\tilde{t}_1 \to c\tilde{\chi}_1^0$ with the small mass splitting $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$, searches in the mono-jet + missing E_T final state provide sensitivities [31, 35]; however, as the mass splitting increases, mono-jet searches lose sensitivities and ATLAS performed a dedicated search with a charm-tagging [35] to fill this gap.

Gaining sensitivities to the top squark production remains difficult especially if $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \sim m_t$. If $m_{\tilde{\chi}_1^0}$ is small, the expected signal looks very similar to the SM $t\bar{t}$ production. ATLAS used the $t\bar{t}$ cross section measurement to place limits on the pair-production of top squarks with each top squark decaying to the top quark and LSP [36]. For higher $m_{\tilde{\chi}_1^0}$ values, CMS considered accessing such scenarios via the cascade decay of the heavier top squark ($\tilde{t}_2$), i.e., $\tilde{t}_2 \to \tilde{t}_1(H/Z) \to t(H/Z)\tilde{\chi}_1^0$ [37]. The results are shown in Fig. 7(b).

The production of charginos and neutralinos are also vigorously searched for by CMS and ATLAS. Searches for chargino-neutralino ($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$) pair production were performed in a variety of final states with leptons and W, Z, and Higgs bosons [38, 39, 40, 41, 42]. These complementary searches provide sensitivities to $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production with decays to left-handed sleptons ($\tilde{\ell}_L$), right-handed sleptons ($\tilde{\ell}_R$), or direct decays to Higgs and vector bosons as shown in Fig 8(a). The sensitivities and mass exclusions strongly depend on the branching fraction of $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$. If $m_{\tilde{\ell}}$ is inbetween $m_{\tilde{\chi}_1^{\pm}}/m_{\tilde{\chi}_2^0}$ and $m_{\tilde{\chi}_1^0}$, the leptonic decay fractions of $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ increase, which enhances the sensitivities. For the scenarios in which $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ decays to W/Z/H, sensitivities from the Run 1 searches are still modest, and the future LHC running will be essential to explore up to the TeV scale as shown in Fig. 9(c).

Searches are also performed in the HH and HZ final states [43]. A signal in these final states is expected from, e.g., the gauge-mediated SUSY model with the higgsino-like $\tilde{\chi}_{1,2}^0$ and $\tilde{\chi}_1^{\pm}$. A pair of $\tilde{\chi}_1^0$ with each $\tilde{\chi}_1^0$ decaying to H/Z and LSP (gravitino $\tilde{G}$), lead to these final states. The covered channels include HH $\to b\bar{b}b\bar{b}, \gamma\gamma(b\bar{b}, ZZ, WW, \tau\tau)$, and HZ $\to \gamma\gamma jj, \gamma\gamma\ell\ell, b\bar{b}\ell\ell$, and searches in these channels provide complementary sensitivities. Exclusions are set on the higgsino mass up to about 380 GeV in case the $\tilde{\chi}_1^0$ dominantly decays to Z and $\tilde{G}$; however, no exclusion is set on scenarios with high $\tilde{\chi}_1^0 \to H\tilde{G}$ branching fractions.

CMS has also performed a generic search for a kinematic endpoint in dilepton (e^+e^- and $\mu^+\mu^-$) mass spectra. If there is a decay process, e.g., $\tilde{\chi}_2^0 \to \ell\tilde{\ell} \to \tilde{\chi}_1^0\ell^+\ell^-$, opposite-sign same-flavor dilepton mass spectra are expected to show an endpoint (edge) at $m_{\mathrm{edge}} = \sqrt{(m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\ell}})(m^2_{\tilde{\ell}} - m^2_{\tilde{\chi}_1^0})}/m_{\tilde{\ell}}$. For this search, the signal and background contributions are determined from a kinematic fit where the dominant flavor-symmetric background is constrained with opposite-sign opposite-flavor ($e^+\mu^-$ and $e^-\mu^+$) leptons. A likelihood fit shown in Fig. 8(b) yields the observed significance of 2.4σ, which is not statistically significant, but it will be interesting to study it further with future runs.

5 Future prospects

The LHC will resume its operation in 2015 with the 13 TeV proton-proton collision energy, and the energy will go up to 14 TeV in the coming years. The energy increase from 8 to 13/14 TeV improves discovery sensitivities for high mass resonances, gluinos, and squarks drastically. The LHC is expected to deliver about 300 fb^{-1} of data by 2022, and the high-luminosity LHC (HL-LHC) will accumulate 10 times more data (i.e., about 3000 fb^{-1}) for the following 10 years after major upgrades of the LHC and CMS/ATLAS detectors. Such high luminosities help improving sensitivities particularly for weakly interacting massive particles produced with low cross sections. As examples, the estimated discovery sensitivities for gluino, top squark, and $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production with 300 and 3000 fb^{-1} of data are shown in Fig. 9.

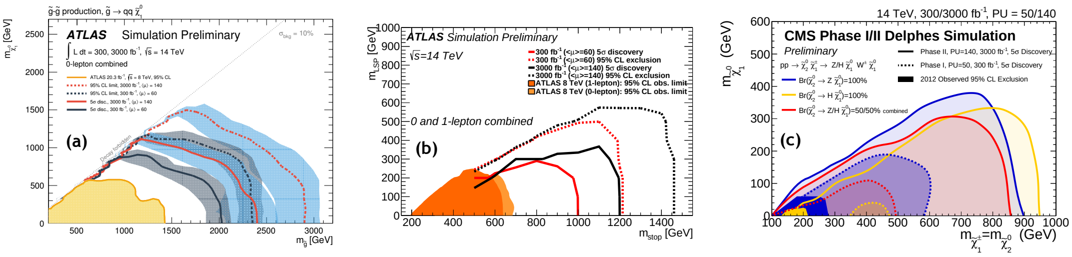

Figure 9: Discovery reaches for supersymmetry with 300 fb^{-1} (LHC Run 2+3) and 3000 fb^{-1} (HL-LHC) for (a) $\tilde{g}$-pair [45], (b) $\tilde{t}_1$-pair [45], and (c) $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production [46].

6 Summary

The CMS and ATLAS collaborations have performed a wide variety of searches for physics beyond the standard model in the LHC Run 1 data. No new physics signature has not been observed yet, and only exclusion limits have been presented. However, our journey of new physics searches at the $\sim$TeV scale have just begun, and the LHC operation in the coming years will provide exciting opportunities to find new physics beyond the standard model.

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