SEARCHES FOR SUPERSYMMETRY IN EVENTS WITH ONE OR MORE LEPTONS USING THE ATLAS AND CMS EXPERIMENTS

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Recent results from searches for supersymmetry in final states with one or more leptons by the ATLAS and CMS collaborations are reported. The data for these results have been recorded in 2015 at $\sqrt{s} = 13\,\text{TeV}$ and amount to an integrated luminosity of $2.2 - 2.3\,\text{fb}^{-1}$ for the CMS experiment and $3.2\,\text{fb}^{-1}$ for the ATLAS experiment. The results are interpreted in simplified models.

1 Introduction

Supersymmetry (SUSY) is generally regarded to be among the most favorite extensions of the Standard Model (SM) of particle physics [1]. SUSY establishes a relationship between fermions and bosons, extending the space-time symmetry group underlying the SM. The existence of the predicted superpartners, which differ in spin by one-half, has not been established, yet. As a consequence, if it is realized in nature, supersymmetry has to be a spontaneously broken symmetry to accommodate superpartners with different masses. As all other properties of SM particles and superpartners are identical, no "unnatural" fine tuning is needed in the Higgs sector, provided that the third generation squarks and the gluino have relatively low masses. This low mass realization of SUSY makes searches for $\tilde{t}, \tilde{b}, \tilde{g}$ at the TeV scale particularly promising. In R-parity conserving SUSY models, the lightest SUSY particle (LSP) is stable and can serve as a candidate for dark matter. As a consequence, typical experimental signatures are high (b-)jet multiplicities and missing transverse energy due to LSPs escaping detection.

In 2015, the LHC Run 2 has started at a center-of-mass energy of 13 TeV. The energy increase with respect to Run 1 leads to a significant enhancement of production cross sections of heavy particles. The gain is particularly high for strong production so that the relatively low integrated luminosity at 13 TeV already enables searches to exclude new regions of the SUSY parameter space.

In this note, the preliminary results of searches by ATLAS and CMS in the single-lepton final state, the same-sign dilepton and three or more lepton final state, and the results of opposite-sign same-flavor dilepton searches are summarized.

2 Searches in the single-lepton final state

Three searches for gluino-pair production with decays into either $\tilde{g} \to t\bar{t}\chi_1^0$ or $\tilde{g} \to qqW\chi_1^0$ have been presented in the talk. One search by the CMS collaboration uses the observable $\Delta\Phi$ (the azimuthal angle between the W-boson candidate (vector sum of the lepton p_T and E_T^miss) and the lepton). It is the most recent public result [2] and complements the CMS analysis using the sum of masses of large-radius jets targeting $\tilde{g} \to t\bar{t}\chi_1^0$ decays [3] and the ATLAS analysis targeting $\tilde{g} \to qqW\chi_1^0$ decays [4].

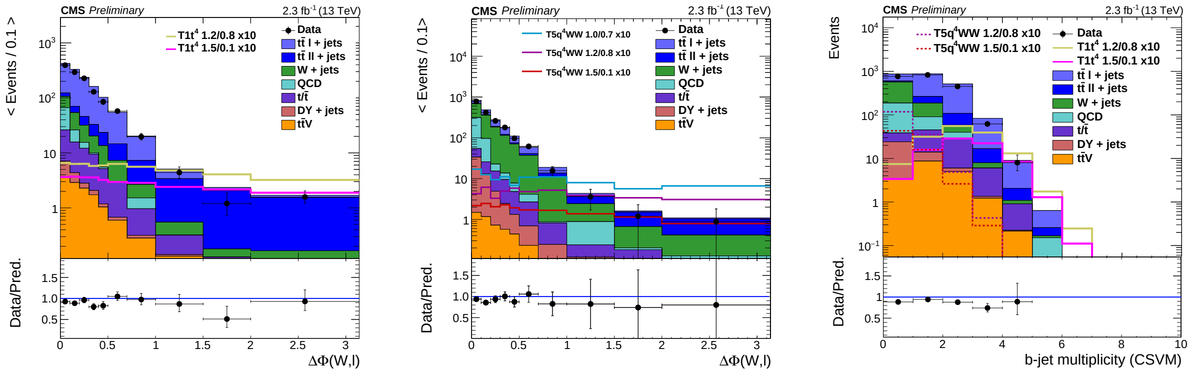

Figure 1 – $\Delta\Phi$ distributions for $n_{\mathrm{b-tag}} = 0$ (left) and $n_{\mathrm{b-tag}} \geq 1$ (center) and full $n_{\mathrm{b-tag}}$ distribution (right), all after the preselection ($H_{\mathrm{T}} > 500\,\mathrm{GeV}$, lepton $p_{\mathrm{T}} > 25\,\mathrm{GeV}$, and $L_{\mathrm{T}} > 250\,\mathrm{GeV}$) [2]. In all plots, the simulated backgrounds are stacked on each other and signal points for $\tilde{g} \to t\bar{t}\chi_1^0$ and $\tilde{g} \to qqW\chi_1^0$ decays are overlayed for illustration without being stacked.

2.1 Search for supersymmetry in events with one lepton in proton-proton collisions at $\sqrt{s} = 13\,TeV$ with the CMS experiment ($\Delta\Phi$ analysis)

The phase space of this search is defined by requirements on the number of jets (n_{jet}), the number of b-tagged jets ($n_{\mathrm{b-tag}}$), the scalar sum of the transverse momenta p_{T} of the jets (H_{T}), and the scalar sum of the lepton p_{T} and the missing transverse energy (L_{T}). All these observables are used to define exclusive search regions with minimal requirements of $H_{\mathrm{T}} > 500\,\mathrm{GeV}$, lepton $p_{\mathrm{T}} > 25\,\mathrm{GeV}$, and $L_{\mathrm{T}} > 250\,\mathrm{GeV}$.

The key observable is $\Delta\Phi$. It is used to separate signal from background: For SM backgrounds with one leptonically decaying W boson, $\Delta\Phi$ has a maximum value, fixed by the mass and p_{T} of the W boson, and accumulates at low values. In contrast, for SUSY events considered as signal, the $E_{\mathrm{T}}^{\mathrm{miss}}$ has sizable contributions from the LSP, leading to an almost uniform $\Delta\Phi$ distribution.

Depending on $n_{\mathrm{b-tag}}$, the sensitivity to $\tilde{g} \to qqW\chi_1^0$ and $\tilde{g} \to t\bar{t}\chi_1^0$ decays is different. To specifically deal with the different background composition, the analysis is split up into a dedicated $n_{\mathrm{b-tag}} = 0$ and $n_{\mathrm{b-tag}} \geq 1$ part. This is also illustrated by Fig. 1, which shows the $\Delta\Phi$ distribution for $n_{\mathrm{b-tag}} = 0$ and $n_{\mathrm{b-tag}} \geq 1$ as well as the full $n_{\mathrm{b-tag}}$ distribution after the preselection. While most of the sensitivity to the $\tilde{g} \to qqW\chi_1^0$ signals is observed for $n_{\mathrm{b-tag}} = 0$, the $\tilde{g} \to t\bar{t}\chi_1^0$ signals are peaking at higher $n_{\mathrm{b-tag}}$.

The background estimation method in both cases is an ABCD method, in which the transfer factor from low $\Delta\Phi$ (background dominated) to high $\Delta\Phi$ (signal dominated) R_{CS} is determined in a low n_{jet} sideband to determine the background in the search regions from the adjacent low $\Delta\Phi$ region. A κ value from simulation is applied to account for the n_{jet} dependence of R_{CS}. While the $n_{\mathrm{b-tag}} \geq 1$ analysis applies an overall R_{CS} value for all backgrounds, the $n_{\mathrm{b-tag}} = 0$ analysis uses one $W+$jets and one $t\bar{t}$ R_{CS} and determines the relative fraction of the backgrounds from a fit to the $n_{\mathrm{b-jet}}$ distribution. The QCD background is estimated separately and subtracted from the low $\Delta\Phi$ control regions before calculation of R_{CS}.

The background predictions and observations are compatible and limits for $\tilde{g} \to qqW\chi_1^0$ and $\tilde{g} \to tt\chi_1^0$ decays are set. These are later compared to the limits of other analyses covered in this note.

2.2 Search for supersymmetry in pp collisions at $\sqrt{s} = 13, TeV$ in the single-lepton final state using the sum of masses of large-radius jets with the CMS experiment

This analysis uses the transverse mass of lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ (m_{T}), and a novel observable M_J (the scalar sum of the masses of large-R jets, inspired by [5]) as main discriminating quantities.

M_J provides discrimination between signal and background. Without initial state radiation

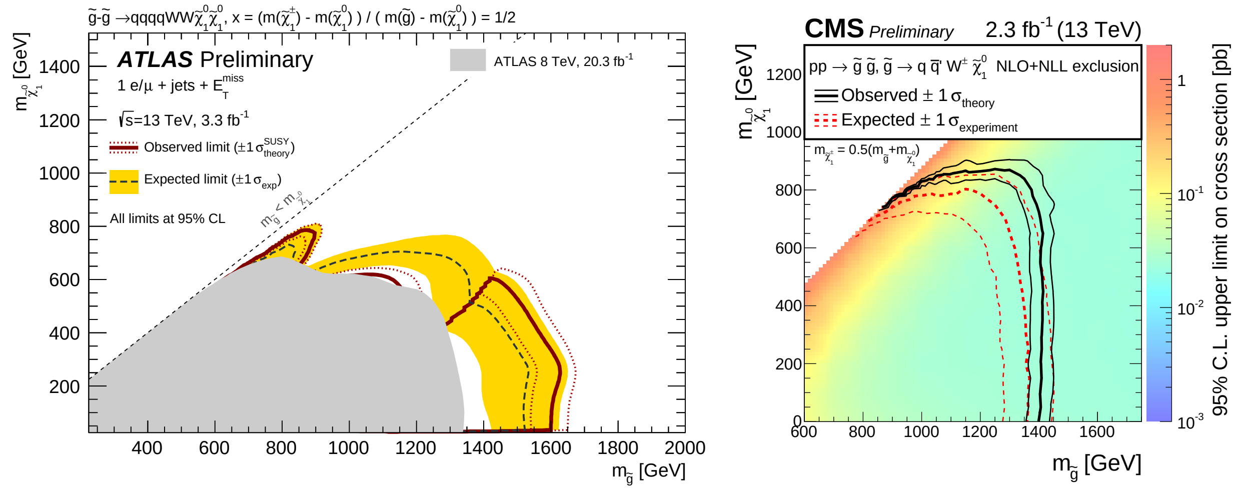

Figure 2 – Left: Cross section limits[4] at 95% CL as a function of the the gluino and LSP masses, using for each model point the signal region with the best expected sensitivity. The exclusion limits by previous ATLAS analyses are shown as gray area. Right: Cross section limits[2] at 95% CL as a function of the the gluino and LSP masses, combining all search regions for the limit determination.

(ISR), there is a clear cut-off of M_J at $\approx 2 \times m_t$ for the dominant $t\bar{t}$ background. This cut-off is smeared out by ISR, but the gluino-pair production signals with $\tilde{g} \to t\bar{t}\chi_1^0$, i.e. four top quarks in the final state, naturally peak at much higher values of M_J.

M_J is also a key part of the background estimation: As M_J is largely uncorrelated to m_{T}, both observables are used to span the plane for an ABCD method background estimate. The search regions are binned in terms of $E_{\mathrm{T}}^{\mathrm{miss}}$, n_{jet}, and $n_{\mathrm{b-jet}}$ and the effect of any residual correlation of M_J and m_{T} is corrected for with κ factors from simulation. Background predictions and observations are compatible and limits for $\tilde{g} \to t\bar{t}\chi_1^0$ decays are shown in Figure 6.

2.3 Search for gluinos in events with an isolated lepton, jets and missing transverse momentum at $\sqrt{s} = 13, TeV$ with the ATLAS detector

This analysis is based on two complementary sets of search channels. The soft-lepton channel targets SUSY models with small mass differences between the predicted supersymmetric particles and the hard-lepton channel ($p_{\mathrm{T}} > 35\,\mathrm{GeV}$) targets large mass differences. Six search regions (all requiring high values of m_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$) are considered in total, each targeting a certain region of the parameter space.

The main backgrounds $t\bar{t}$ and $W+\mathrm{jets}$ are determined by normalizing the MC prediction in control regions while small backgrounds are taken directly from the simulation.

The results of the analysis are interpreted for $\tilde{g} \to qqW\chi_1^0$ decays in gluino-pair production and the expected limits significantly exceed the 8 TeV results. A slight excess in the muon channel of the 6-jet region reduces the observed limits. In Figure 2, these limits are compared to the corresponding CMS results presented in Section 2.1.

3 Searches in the same-sign dilepton and multilepton final states

Final states with same-sign dileptons and three or more leptons are rare in the SM. As a consequence, searches for physics beyond the SM in these final states can be very powerful and provide a broad sensitivity to many SUSY scenarios with leptons in the final state. They complement other analyses' sensitivity and play a particularly important role in models with longer decay chains of SUSY particles favoring higher lepton multiplicities or small mass splittings of the LSP and squarks/gluinos.

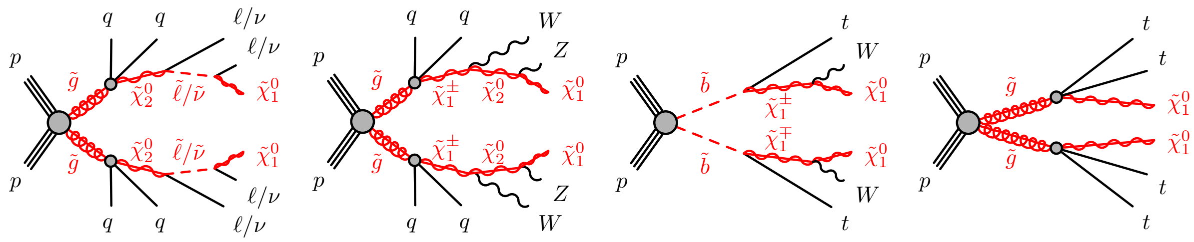

Figure 3 – SUSY processes considered by the SS/multilepton analysis [6] for optimizing signal regions and setting limits.

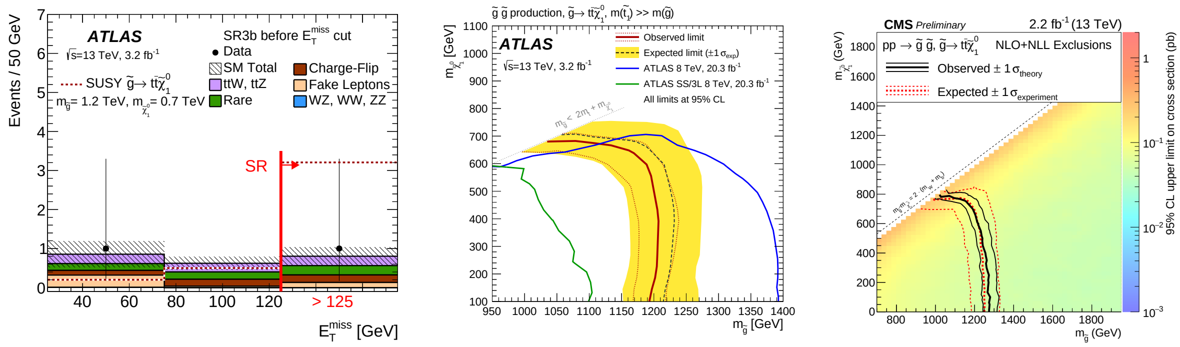

Figure 4 – Missing transverse energy distribution of the SR3b selection before the final E_T^{miss} cut (left); resulting limits on the gluino and neutralino masses for $\tilde{g} \to t\bar{t}\chi_1^0$ decays of the ATLAS [6] (center) and CMS [7] (right) analysis.

Key to these analyses is to suppress and estimate the low reducible backgrounds such as misidentified and non-prompt leptons and charge-flipping for electrons. Data-driven estimates are used in all analyses covered here [6,7,8].

3.1 Search for supersymmetry at $\sqrt{s} = 13$ TeV in final states with jets and two same-sign leptons or three leptons with the ATLAS detector

This analysis [6] presents a search for strongly produced SUSY particles in final states with multiple energetic jets and either two isolated leptons (e or μ) with the same electric charge (SS) or at least three isolated leptons (multilepton).

Four signal regions are chosen in the analysis, each aiming at one of the signal models summarized in Figure 3. For the case of a light third generation, two signal regions with b-jet requirements are defined, while two other signal regions are defined with a b-jet veto, aiming at decay chains of gluinos to light quarks and leptons. Besides different $n_{\mathrm{b-tag}}$ requirements, the signal regions are characterized by the lepton and jet multiplicity, requirements on $E_{\mathrm{T}}^{\mathrm{miss}}$ and m_{eff} (scalar sum of the p_{T} of the signal leptons and jets in the event plus $E_{\mathrm{T}}^{\mathrm{miss}}$).

As an example, the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution of the SR3b selection aiming at $\tilde{g} \to t\bar{t}\chi_1^0$ decays is shown in Figure 4, as well as the corresponding limits of this analysis and the corresponding CMS analysis [7]. The limits significantly exceed the 8 TeV results of the corresponding analysis, excluding gluino masses of up to 1200 GeV. In addition, they extend the reach beyond the combination of all 8 TeV ATLAS results in the compressed region. The reach of the multi-bin CMS analysis is comparable and is also shown in Figure 4.

3.2 Search for SUSY with multileptons in 13 TeV data with the CMS experiment

This CMS analysis [8] targets very similar signal models as the SS analyses presented earlier. In this multi-bin analysis, the events are categorized based on $n_{\mathrm{b-tag}}$, H_{T}, $E_{\mathrm{T}}^{\mathrm{miss}}$, and whether there are on-Z lepton pairs in the event. A total of 30 signal regions are considered for the final result. No significant excess has been found and limits in various signal models have been set.

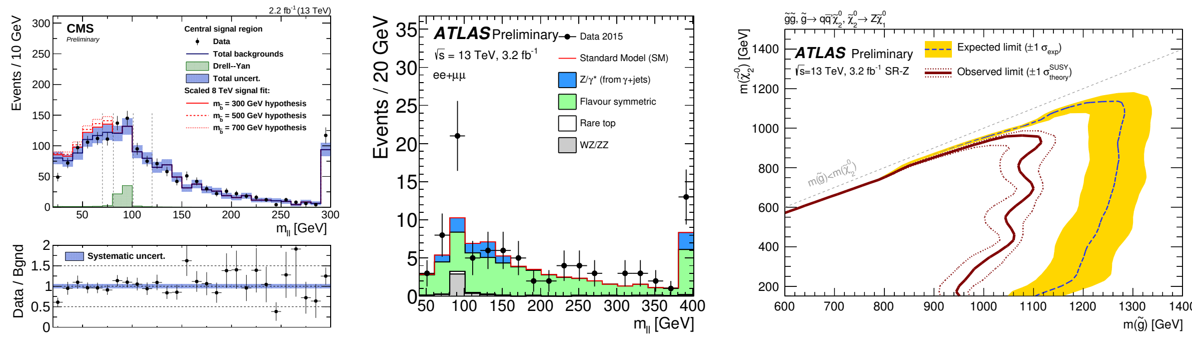

Figure 5 – Left: The dilepton invariant mass distribution for the off-Z selection. The signal shape measured by CMS with 8 TeV data has been overlaid on top of the background prediction for three different sbottom mass hypotheses [11]. Center: The dilepton invariant mass distribution in the same-flavor channels. The MC prediction is showing the expected shape of the distributions. A similar excess to that observed at 8 TeV [10] is visible in data [12]. Right: The excess in the on-Z region leads to a significantly reduced observed limit in the $m(\chi_2^0)/m(\tilde{g})$ plane [12].

For example, the limit for $\tilde{g} \to t\bar{t}\chi_1^0$ decays is comparable to those shown in Figure 4 for the SS analyses and included in Figure 6.

4 Searches in the opposite-sign same-flavor (OSSF) dilepton final state

In the OSSF dilepton final state, the analyses of 8 TeV data [9,10] by ATLAS and CMS showed excesses over the SM expectations: ATLAS reported a 3σ excess in the on-Z region that can be interpreted in SUSY models with a large neutralino mass difference. CMS reported a 2.6σ excess in the off-Z region that can be interpreted in SUSY models with off-shell Z-boson or slepton decays that lead to a characteristic edge shape in the dilepton mass distribution. Both experiments have revisited these excesses with 13 TeV data.

4.1 Search for new physics in final states with two opposite-sign same-flavor leptons, jets and $E_T^{\rm miss}$ in pp collisions at $\sqrt{s} = 13$ TeV with the CMS experiment

The analysis [11] includes additional event categories for the on-Z and off-Z searches beyond those in the 8 TeV analysis to increase sensitivity to new physics. It has revisited both moderate excesses observed at 8 TeV and explicitly included an ATLAS-like search region in order to enable a more direct comparison of the results.

The observations in all signal regions, including those with 8 TeV excesses in the on-Z (ATLAS) and the off-Z region (CMS), are consistent with SM expectations. The dilepton invariant mass distribution for the off-Z selection is shown in Figure 5 and includes the signal shape extracted from 8 TeV. In the ATLAS-like search region, no excess has been observed over the expectation of 12 events (12 observed).

4.2 A search for Supersymmetry in events containing a leptonically decaying Z boson, jets and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector

The analysis [12] performs a search for OSSF lepton pairs with an invariant mass consistent with that of the Z boson, jets and large $E_T^{\rm miss}$. It updates the previous search at 8 TeV [10], in which an excess of 3σ over SM expectations was ascertained.

As illustrated in Figure 5, 21 events are observed in the on-Z region in the 13 TeV analysis with a predicted background of 10.3 events. This excess corresponds to a significance of 2.2σ. As a consequence, the observed limit in the $m(\chi_2^0)/m(\tilde{g})$ plane is significantly reduced with respect to the expected limit.

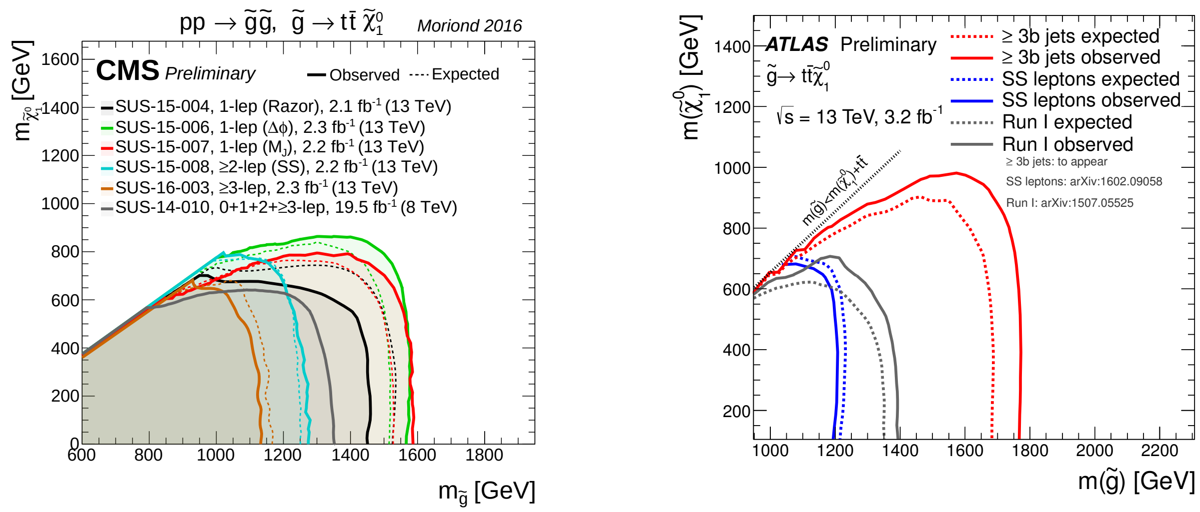

Figure 6 – Left: Summary plot of the limits on gluino-pair production with the decay $\tilde{g} \to t\bar{t}\chi_1^0$ set by leptonic CMS analyses using 13 TeV data. Right: Summary of limits for the same model set by the ATLAS same-sign dilepton analysis [6] and an inclusive search [13] requiring $n_{\mathrm{b-tag}} \geq 3$.

5 Conclusions

The new data collected at a center-of-mass energy of 13 TeV provides important insights, even though the integrated luminosity is much lower than that of the 8 TeV dataset. A broad set of searches for SUSY with leptons in the final state has been performed by ATLAS and CMS. Limits of the gluino-pair production with $\tilde{g} \to t\bar{t}\chi_1^0$ decays could be pushed by about 300 GeV to more than 1700 GeV as illustrated in Figure 6. The excesses in the OSSF dilepton final state observed by ATLAS and CMS in different kinematic regions at 8 TeV have been revisited, but no conclusion on the on-Z excess can be drawn, yet.

The quick ramp-up of the instantaneous luminosity delivered by the LHC during Run 2 will enable ATLAS and CMS to quickly surpass the results from 2015 data and Run 1 with an expected integrated luminosity of the order of 30 fb^{-1} in 2016. Hints for new physics from 2015 data will be carefully scrutinized with this large dataset.

References

1. Stephen P. Martin, arXiv:hep-ph/9709356 (1997)
2. CMS Collaboration, CMS-PAS-SUS-15-006 (2016)
3. CMS Collaboration, CMS-PAS-SUS-15-007 (2015)
4. ATLAS Collaboration, ATLAS-CONF-2015-076 (2015)
5. Anson Hook et al., *Phys. Rev.* D **85**, 055029 (2012)
6. ATLAS Collaboration, arXiv:1602.09058 (2016)
7. CMS Collaboration, CMS-PAS-SUS-15-008 (2015)
8. CMS Collaboration, CMS-PAS-SUS-16-003 (2016)
9. CMS Collaboration, JHEP **04**, 124 (2015)
10. ATLAS Collaboration, Eur. Phys. J. **C75**, 318 (2015)
11. CMS Collaboration, CMS-PAS-SUS-15-011 (2015)
12. ATLAS Collaboration, ATLAS-CONF-2015-082 (2015)
13. ATLAS Collaboration, ATLAS-CONF-2015-067 (2015)