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SEARCHES FOR PHYSICS/PARTICLES BEYOND THE STANDARD MODEL AT THE LHC*

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One of the main goals of the LHC is a search for phenomena beyond the Standard Model. Some basic aspects of such searches at the ATLAS and the CMS, two universal LHC detectors are recalled. Results of two representative analyses are shown and the importance of the search for dark matter candidates is underlined.

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1. Introduction

Searches for phenomena beyond Standard Model (BSM) are the primary goals of the ATLAS and CMS experiments utilizing two multi-purpose detectors at the LHC.

BSM searches at the LHC are organized into two big subgroups: SUSY (supersymmetry) and EXO (Exotics at the ATLAS and Exotica at the CMS). The latter is a short name for all non-(mainstream) SUSY. In the CMS, Exotica was divided further to establish Beyond 2 Generation (B2G) subgroup.

Ever growing sets of public results are accessible *via* portals maintained by the ATLAS[1] and the CMS[2] collaborations. Each experiment published about 150 search papers based on data collected during the first LHC phase in which proton–proton collision energy was 7 (in 2011) and 8 TeV (in 2012) and none BSM phenomenon has been found yet.

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[*] Based on the talk on behalf of the CMS and the ATLAS collaborations presented at the XXXIX International Conference of Theoretical Physics "Matter to the Deepest", Ustroń, Poland, September 13–18, 2015.

[1] `https://twiki.cern.ch/twiki/bin/view/AtlasPublic`

[2] `http://cms-results.web.cern.ch/cms-results/public-results/publications`

Some results are still preliminary, whereas fresh 13 TeV *pp* data are coming. Cross sections for massive particle production grow with collision energy and the grow is faster for more massive particles. More than 2/fb of 13 TeV *pp* data per experiment were registered and about one more inverse femtobarn is expected this year. Preliminary results based on these new 13 TeV data will become available soon. As a result, it is more and more difficult for outsiders to follow this inflow of information. I will give below some very basic guidelines meant for newcomers to the field.

To perform searches for direct BSM phenomena, apart from the well performing collider operating at the highest possible energy (LHC), an efficient, precise and well understood multi-purpose detector is needed (ATLAS or CMS). In each search paper, there are references to detector specific information and methods used in the analysis, but it is much more efficient to look for an assistance by insiders than to struggle with a substantial chain of references in a case when such information is crucial *e.g.* for an interpretation of the search results within a model not taken into account in the analysis itself. Contact with conveners of appropriate search subgroup could be very helpful in such a case.

All searches are designed to be as model independent as possible. The search is defined by its topology, but several topologies for one phenomenon are possible and *vice versa* several phenomena could be searched for using a given topology. These topologies are based on physics objects (jet, $E_{\mathrm{T}}^{\mathrm{miss}}$, leptons, photon). It is very important to validate these objects using data, to asses their performance, monitor time stability *etc.* For some searches custom objects are used (long-lived particles , monopoles *etc.*).

If one is going to design new search topology, the first step is to consider what trigger could be employed. Trigger implementations differ between ATLAS and CMS, but one can distinguish (final) high level trigger (HLT) working online on computer farm at the detector proximity and reducing the rate to the level acceptable by the data acquisition system (few hundreds Hz) and low level (first level) instrumental trigger which must decrease the rate to the level accepted by the HLT (kHz level). One should remember that no search is possible without the first level trigger (see *e.g.* Sec. 4).

A typical search uses signal sensitive variables (at least two if possible). One (or several) Signal enriched Regions (SR) are defined (both criteria satisfied). The remaining parts of the phase space form Control Regions (CR) in which at least one criterion is not satisfied. Data driven methods are (preferably) used to find out and validate transfer factors from CR to SR to obtain a data driven estimate of background level in the SR (including background systematics not explained here), however, sometimes it is necessary to use Monte Carlo (MC) sample to estimate the level of background. The search analysis is usually much more complicated if a ‘shape analysis’ is used instead of a ‘simple counting experiment’.

2. Search for supersymmetry at the LHC

Supersymmetry could be regarded as a benchmark for general BSM searches because it is difficult to find topology which is not used for SUSY searches. For the same reason, many such searches could be reinterpreted in other models. Canonical signature for models with conserved R parity is a presence of missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$. Broad spectrum of analyses span from inclusive searches for significant $E_{\mathrm{T}}^{\mathrm{miss}}$ accompanied by a given number of jets, leptons or photons via targeted searches for specific scenarios to exploration of challenging (*e.g.* compressed spectra) or less standard (RPV, non-prompt decays *etc.*) ones.

The fact that SUSY was not yet discovered at the LHC underlines importance of more difficult, from experimental point of view, scenarios. What is under permanent development is triggering on soft signals, new kinematic variables, multivariate analyses, novel background suppression methods, background estimation (using data driven methods whenever possible), background systematics (which limits sensitivity for challenging scenarios) *etc.*

Searches are inspired and/or interpreted in specific models (CMSSM, NUHM, NMSSM *etc.*) but recently also in the so-called phenomenological MSSM (pMSSM) [2] (with 19 parameters instead of more than 100 present in the MSSM) or so-called Simplified Models Spectra (SMS) [3, 4] (effective descriptions in which only very few lightest supersymmetric partners are accessible at the LHC).

Examples of SMS diagrams are shown in figure 1, and interpretation of a search for this 3 lepton topology are plotted (as outer most contours) in figure 2 (CMS) and in figure 3 (ATLAS) together with many more exclusions obtained for different topologies addressed in publications [1, 5–7], when searching for production of so-called electroweakinos at 8 TeV LHC.

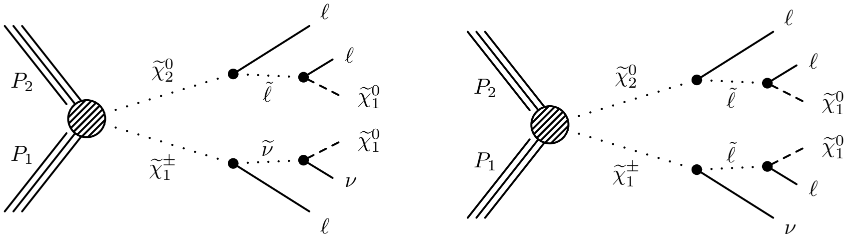
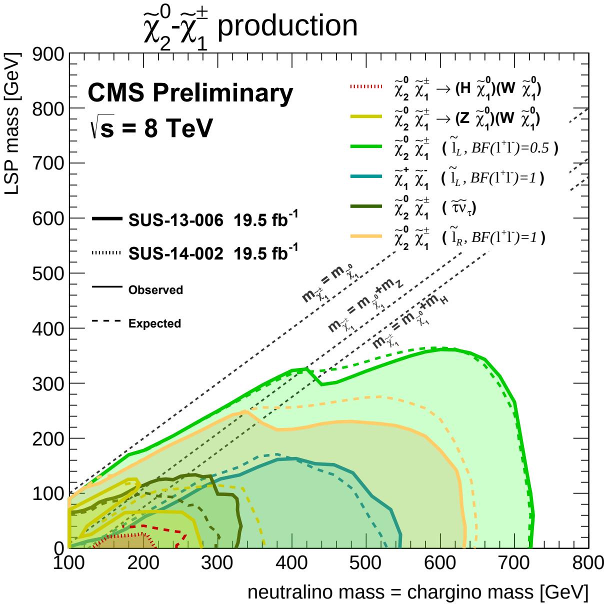


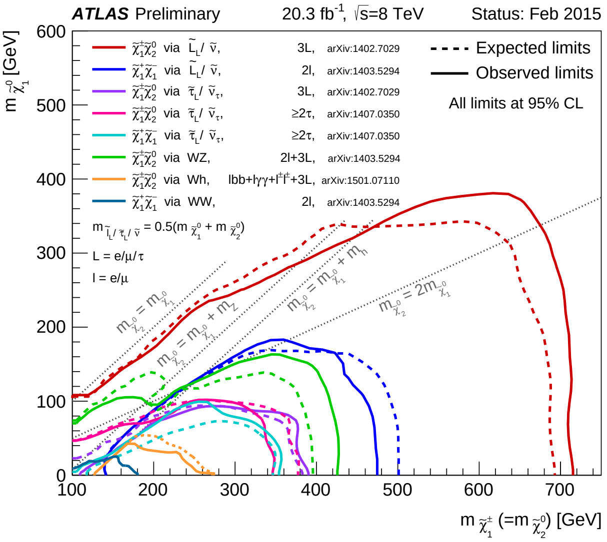
Fig. 1. Chargino–neutralino pair production with decays mediated by sleptons and sneutrinos, leading to a three-lepton final state and $E_{\mathrm{T}}^{\mathrm{miss}}$ [1].

First data recorded at 13 TeV were already used by SUSY subgroups to study performance of some analysis chains [8–11].



`twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsSUS/EWKino_ICHEP2014_2.pdf`

Fig. 2. Summary of CMS searches for electroweak production of charginos and neutralinos based on 19.5/fb of pp collision data at $\sqrt{s} = 8$ TeV [1, 5].



`atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/ATLAS_SUSY_EWSummary/ATLAS_SUSY_EWSummary.pdf`

Fig. 3. Summary of ATLAS searches for electroweak production of charginos and neutralinos based on 20/fb of pp collision data at $\sqrt{s} = 8$ TeV [6, 7].

3. Exotica searches at the LHC

Within this subgroup signals, predicted by large number of different models are searched for: extra dimensions, microscopic black holes, new gauge bosons, contact interactions, leptoquarks, heavy quarks, excited fermions,

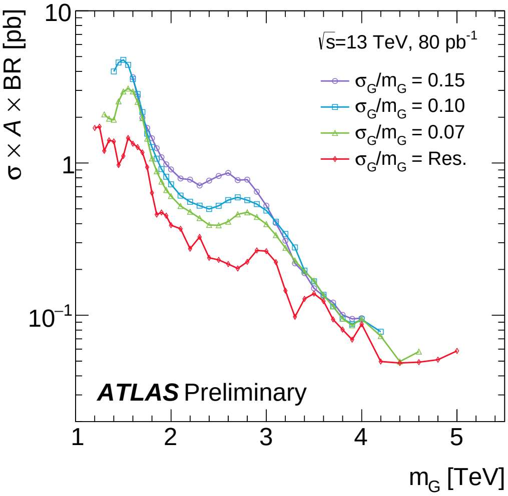


Fig. 4. Summary of ATLAS dijet 13 TeV. The 95% C.L. upper limits obtained in the resonance analysis for a hypothetical signal that produces a Gaussian contribution (with four different widths) to the observed dijet mass distribution (m_{G}) [12].

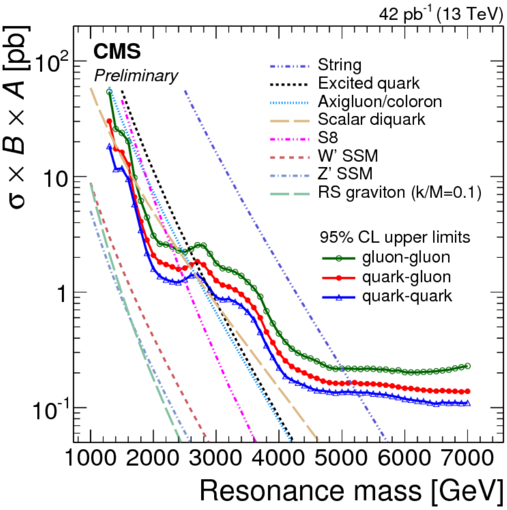


Fig. 5. The observed 95% C.L. upper limits for dijet resonances of the type gluon–gluon, quark–gluon, and quark–quark, compared to several predictions [15].

dark matter (see Sec. 4), multi-jet resonances, long lived particles (CMS, at ATLAS SUSY LLP are searched for within the SUSY subgroup) and many others. For some searches, cross sections at 13 TeV are sufficiently large to challenge 8 TeV limits [12–15].

Some examples are shown in figure 4 (ATLAS) and figure 5 (CMS), where exclusions obtained when searching for massive dijet resonances are presented.

4. Search for dark matter at the LHC

One of the best motivated BSM searches is that for dark matter (DM) candidates. In fact, almost all BSM searches could be regarded as such, because in most of the BSM models there are DM candidates of some kind. However, so-called direct and indirect DM searches are meant for Weakly Interacting Massive Particles (WIMPs) of which LSP neutralino is a generic example. As it is schematically shown in the left part of figure 6 the same diagram governs these searches and DM pair productions at colliders. However, something detectable must be radiated from the initial state to trigger on such events (the right part of the same figure).

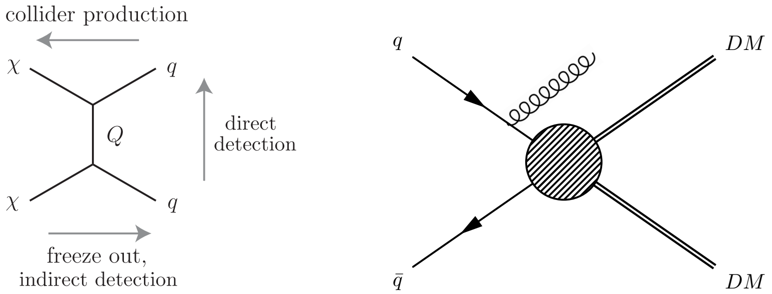


Fig. 6. The same diagram corresponds to direct, indirect and collider searches for dark matter [16] (left). An ISR gluon (or anything detectable) is needed to trigger on DM pair production at colliders [17] (right).

An example of comparison of collider results with the direct DM searches is shown in Fig. 7 for spin-independent and in Fig. 8 for spin-depended interactions. It could be seen that collider searches are competitive for small DM masses and up to 1 TeV for spin-depended case. However, to fully exploit collider potential, it is necessary to go beyond effective theory and resolve DM interaction with ordinary matter. The details could be found in the Report of the ATLAS/CMS Dark Matter Forum [19].

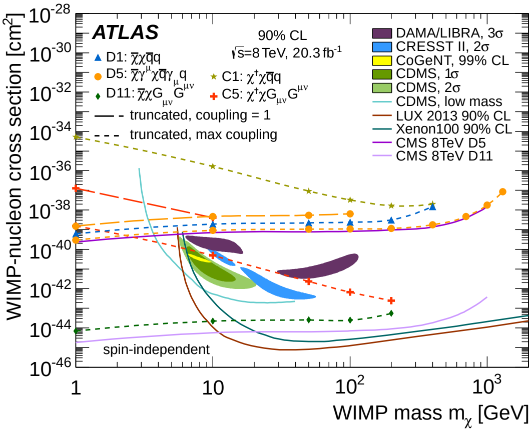


Fig. 7. Search for dark matter in mono-jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ topology in the ATLAS [18] compared to selected direct (spin-independent) searches and corresponding earlier search by the CMS [17].

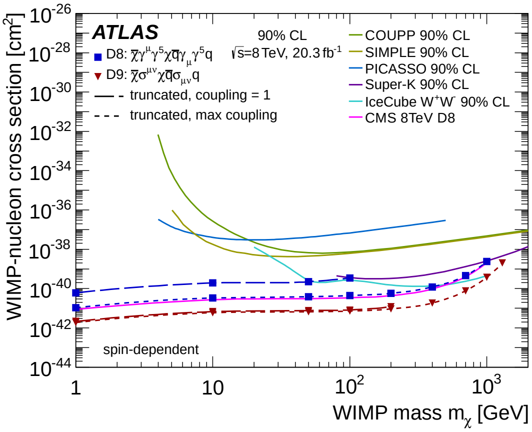


Fig. 8. Search for dark matter in mono-jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ topology in the ATLAS [18] compared to selected direct (spin-depended) searches and corresponding earlier search by the CMS [17].

What is even more important is that if DM particles are super weakly interacting (like gravitino), then the LHC is the only place to look for such scenarios in the foreseeable future.

5. Summary

Despite the multitude of search topologies no signal of phenomena beyond the Standard Model has been found at the LHC so far. However, we have no other possibility right now to look for the majority of them and, moreover, we have just started to accumulate data at the proton–proton collision energy of 13 TeV, which was never available before. We do everything to perform the searches in the most optimal way, hoping that New Physics is within our reach.

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