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Search for unconventional final states at ATLAS and CMS

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Abstract

Unconventional searches for new physics performed using proton proton collisions recorded by ATLAS and CMS experiments are shown. Two model independent searches designed to reduce theories dependency and increase the sensitivity for new discoveries are presented together with searches for black holes and long lived particles.

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Search for unconventional final states at ATLAS and CMS

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Unconventional searches for new physics performed using proton proton collisions recorded by ATLAS and CMS experiments are shown. Two model independent searches designed to reduce theories dependency and increase the sensitivity for new discoveries are presented together with searches for black holes and long lived particles.

1 Introduction

The standard model of particle physics is a powerful theory that allows the prediction of a wide range of high-energy phenomena. However, open questions related to the electroweak symmetry breaking, as the hierarchy problem, are still present and many new theoretical models have been proposed. The ATLAS and CMS experiments [1,2] are general purpose experiments that are trying to answer to these questions, by looking for new phenomena. Generally the data recorded by these experiment are analyzed looking for new physics in defined final states where the known particles are reconstructed: for example new resonances decaying to known standard model particles. Furthermore analyses are mostly looking for particles generated and decaying at the interaction point. This strategy is highly model dependent and is not sensitive to unconventional particles as long-lived particles, so that alternative approaches (unconventional) have been studied.
In section 2, two searches for new physics performed at ATLAS and CMS using a model independent approach will be presented. In section 3, a search for black holes at CMS will be presented, while in section 4, the techniques developed to look for long-lived particles will be described. Finally, the conclusions are drawn in section 5.

2 Model independent searches

Numerous analyses are usually targeting specific final states, looking for new physics under the assumption of a particular theory. As a consequence only limited parts of the possible phase space given by the new particles properties, such as masses, decays, productions, cross sections is investigated. Indeed this phase space can be too big, if all the models introduced by theorists

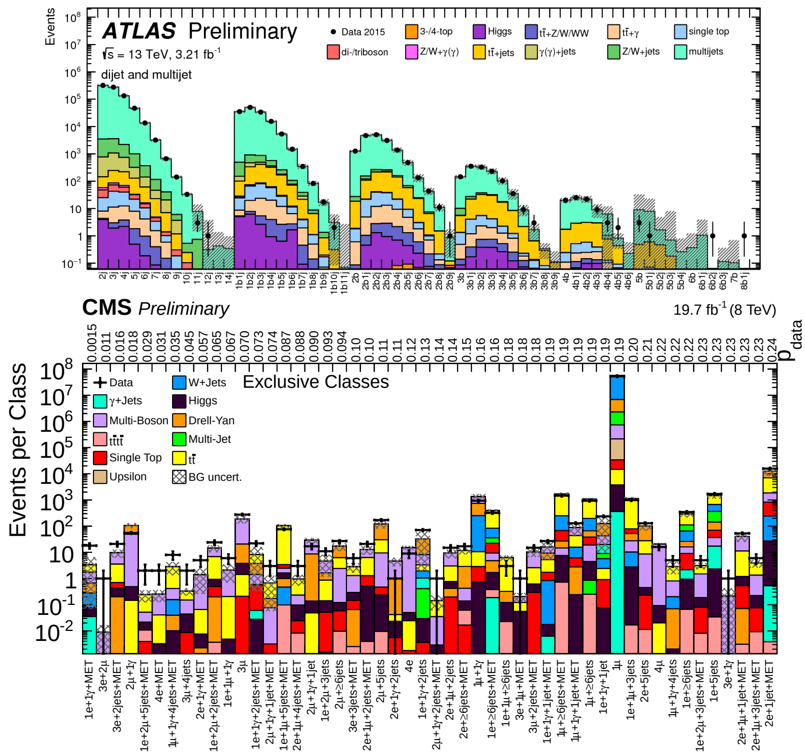

Figure 1 – Comparison between observation and simulation for dijet and multijet events in ATLAS [3] (top) and for the most significat classes in CMS [4] (bottom).

are considered. Because of this, both ATLAS and CMS have been developed the possibility to look for new physics in a model independent way [3,4]. In this approach no selections containing assumptions on a particular phenomena are considered, but only basic objects identification criteria are applied. The events passing the trigger requirements are then classified depending the reconstructed objects multiplicity so that several classes are defined depending on the numbers of electrons, muons, photons, jets, and b jets, and on the missing energy that are present in the event. Then for each of the defined class, the observations are compared with the prediction from the simulation to look for deviations.

The CMS analysis, called MUSiC (Model Unspecific Search in CMS), has analyzed the 8 TeV data recorded in 2012 and corresponding to a luminosity of 20 fb^{-1}. This analysis is using triggers containing isolated leptons: single electron, single muon, double electrons or double

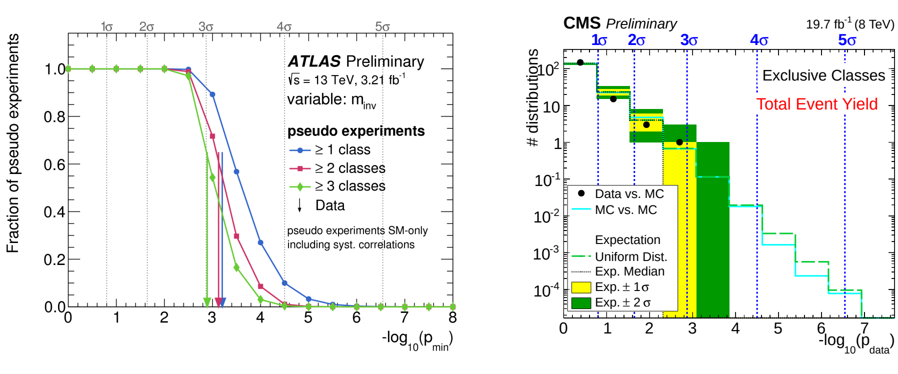

Figure 2 – Left: fraction of pseudo-experiments in which the p-value is smaller than the one in data for the ATLAS analysis [3]. Right: Distribution of p-values for CMS event classes [4].

muons triggers. On the other side, ATLAS has analyzed the 3.2 fb^{-1} recorded during the 2015 data taking and it is using triggers requiring presence of missing energy, single muon, single electron, single photon, double photons or single jet. In figure 1, comparison between observation and prediction for some of the classes of the two analyses are shown. In both cases, after the events are divided in classes, regions of excess or deficit are looked for in peculiar distributions, such as invariant mass of the objects in the event or sum of the p_T of the objects or in the missing energy distribution. To determine these regions, a p-value is calculated in order to quantify the data to MC agreement, and for each class and each distribution, the region with the smallest one is selected. The p-values in data are then compared with the p-values obtained from pseudo-experiments where the data are replaced by pseudo-data which are generated according to the SM expectation. The results are shown in figure 2. For both ATLAS and CMS, no significant deviations are found in data: for ATLAS, the largest discrepancy is expected in about 70% of the pseudo-experiments, while for CMS, the largest discrepancy is found in the class with one electron, one photon and missing energy with a p-value of 0.0015 corresponding to around 3.0σ.

3 Black holes at CMS

In this section an analysis performed by CMS using 2.2 fb^{-1} of data recorded in 2015 is shown[5]. The analysis is looking for new physics in final state inspired by production of microscopic black holes, but it is also interpreted as a generic search that can probe large number of theories, reducing the theory dependence of the analysis as we have seen in the previous section. Black holes production at LHC is predicted by several theories and it results in a number of different final states: in fact the black holes can quickly decay with same probability into hadrons (jets), leptons, photons, etc. The CMS experiment is looking for black holes using as discriminating variable S_T, i.e. the scalar sum of transverse energies of all the reconstructed objects in an event (jets, leptons, photons and missing transverse energy). The events passing the trigger, based on the scalar sum of objects transverse momenta (H_T), are then categorized in several inclusive object multiplicity bins (events where there are at least $\mathrm{N_{min}}$ objects). The major background contribution is given by QCD multijets for which the estimation is performed by looking at lower multiplicity categories, where the signal contamination is expected to be low: the background shape is obtained from the S_T distributions between 1400 and 2400 GeV for categories with N

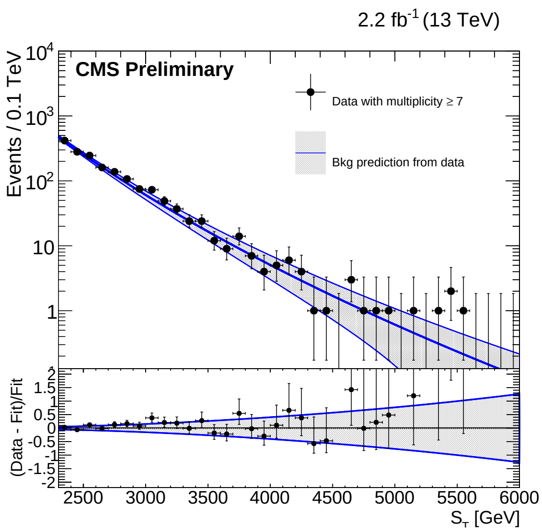

Figure 3 – Comparison between observation and background prediction for the S_T variable in events with reconstructed object multiplicity equal or higher then 7[5].

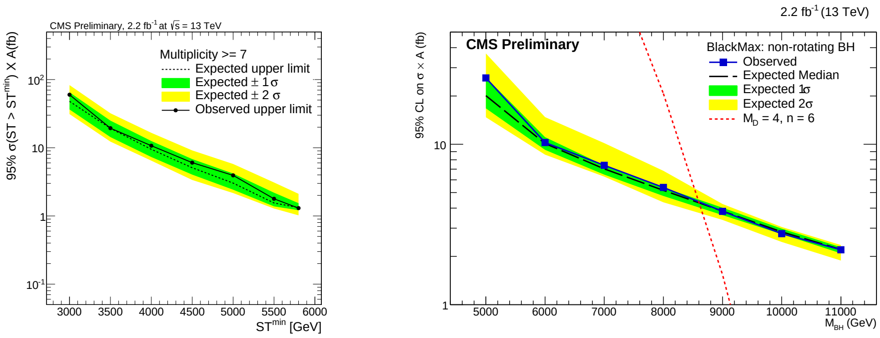

Figure 4 – Left: Model-independent upper limits on the cross section times acceptance for the N $\geq$ 7 case [5]. Right: Observed and expected upper 95% CL limits on the cross section times acceptance for the production of quantum black holes [5].

$\geq$ 2 and 3 and it is then rescaled to higher multiplicity by using normalization factors calculated in lower S_T regions. In figure 3, a comparison between observation and background prediction is shown for one of the categories of the analysis, i.e. the one in which the reconstructed object multiplicity of the events is equal or higher than 7. Since no excess of data events is observed with respect to the background prediction in any of the categories, upper limits new physics production cross sections are set for the two cases of model independent and model dependent search. In the first case (figure 4 left), the limits are on the signal cross section times acceptance for production of new physics with a minimum number of objects and a minimum S_T: these limits can then be used to constrain several signal hypotheses resulting in a multiobject final state. Instead in figure 4 (right), upper limits on the production of quantum black holes are shown in a specific model that predicts the presence of black holes.

4 Long lived particles

An interesting unconventional signature that can appear in many proposed theoretical models is given by heavy charged long lived particles. An example is given by supersymmetry models that introduce new particles called R-hadrons. R-hadrons are composite states of a gluino and SM quarks or gluons for which the gluino can decay with a lifetime with the order of nanoseconds or more, to $q\bar{q}$ and a stable neutralino, that leave the detector undetected. The R-hadrons can be predicted to be charged and with a large mass. This characteristics will give a peculiar signature in the detector for which the standard particle identification algorithms at hadron collider experiments are not designed because they assume particles with speed close to the

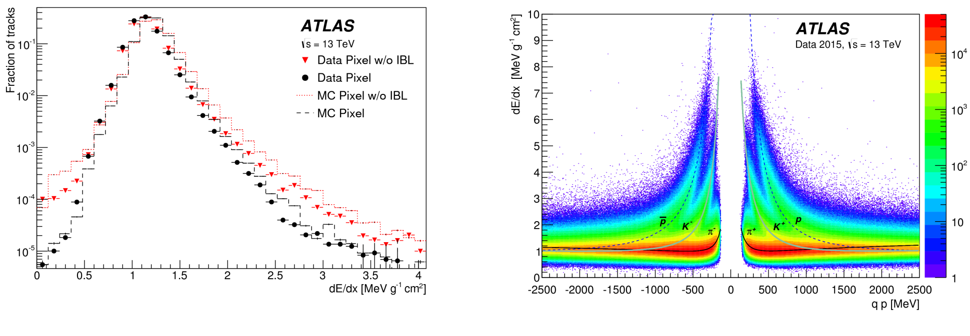

Figure 5 – Left: comparison between data and simulation for the dE/dx distributions as measurement by the ATLAS pixel detector with and without the additional layer [6]. Right: distribution of dE/dx versus the charge signed momentum (qp) for minimum-bias event tracks [6].

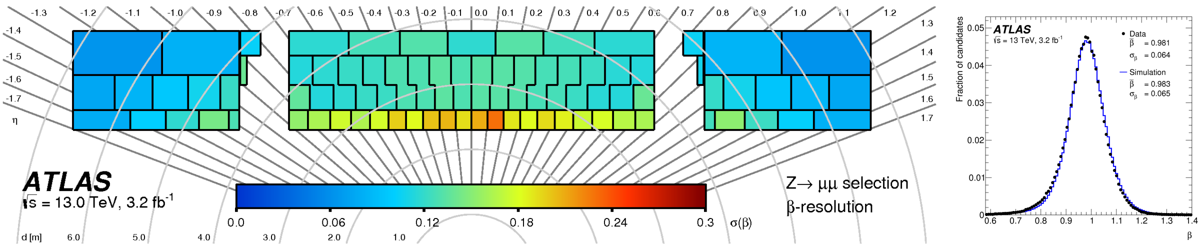

Figure 6 – Left: β resolution for the varius hadronic caloremeters cells as obtained $Z \to \mu\mu$ events [7]. Right: comparison between observation and prediction for the β distribution for muons from the Z decay [7].

speed of light and a charge of 1,as it is the case of standard model particles. On the other side, the peculiar characteristics of charged massive long lived particles can be used to reduce the background, since these new particles are expected to have a speed, β, well below 1, while for standard model particles it is expected to be around 1; and in case of their existence, they leave a larger ionization energy loss, dE/dx, when traversing a material with respect to the standard particles. The ATLAS and CMS collaborations have developed several techniques for these measurements, using the subdetectors to measure β and dE/dx.

The measurement of dE/dx is done by the ATLAS pixel detector in which the clusters leaved by a particle can be used to reconstruct the energy loss of the particle itself. With respect to Run 1, the dE/dx measurement has been improved thanks to the insertion of an additional layer. In figure 5, the dE/dx distribution is shown in data and simulation as measured by the ATLAS pixel subdetectors for minimum-bias event tracks.
In ATLAS, the speed β is measured using timing and distance information from the cells of the hadronic calorimeter, as shown in figure 6 (left). The calibration is performed using muons from the decay of the Z boson (figure 6, right). The β resolution varies between 0.06 and 0.23 depending on the hadronic calorimeter cells.
Two analyses have been presented by the ATLAS Collaboration using 3.2 fb^{-1} of data from the 2015 data taking and looking for R-hadrons with the experimental techniques that have been just described. The analysis described in reference [6] makes use only of the dE/dx measurement in order to search for stable and metastable R-hadrons. Events are selected by a trigger requiring missing transverse momentum, that is expected to be high due to the presence of the neutralino from the gluino decay. After the trigger, the events are selected if a high-p_T isolated track is present. Additional requirements are applied to veto hadrons, electrons and muons. Then the track is required to have a large ionization loss in the pixel detector and the mass is reconstructed thanks to the Bethe-Bloch formula that link the dE/dx to the mass of the ionization particle.

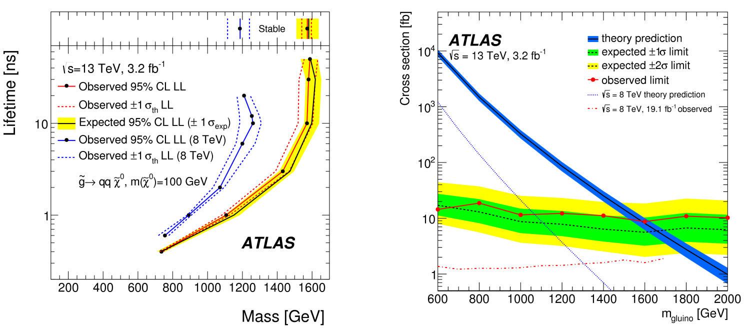

Figure 7 – ATLAS results for R-hadrons searches. On the left, exclusion for stable and metastable R-hadrons for an analysis that uses the dE/dx measurement [6]. On the right, exclusion for R-hadrons for an analysis that uses both dE/dx and β measurements [7].

The expected background is derived from data, generating (p, η, dE/dx) triplets in control regions obtained by inverting some cuts of the signal selection and in which the correlation between the three variables is maintained. After calculating the mass of the particle using these three variables, the distribution is normalized with a factor obtained at low mass, where the signal is expected to be low. No evidence of a signal above the background is observed, so limits are set as shown in figure 7 (left). Gluino R-hadrons are excluded with masses below the range from 740 GeV to 1570 GeV depending on the lifetime, that varies between 0.4 ns to 50 ns. Furthermore also stable R-hadrons are excluded for masses below 1570 GeV.
The second analysis looking for R-hadrons performed by ATLAS and using 2015 data, makes use of both the dE/dx (from which $\beta\gamma$ is evaluated) and the β measurements [7]. Events are selected online by a trigger that requires the presence of high missing energy and offline by the presence of a high-p_T track passing several quality criteria. The final event selection requires upper cuts on β and $\beta\gamma$, i.e. $\beta < 0.75$ and $\beta\gamma <1.35$ (1.15) for R-hadron masses below (greater than) 1.4 TeV. The β and $\beta\gamma$ variables are used to extract the two masses m_β and $m_{\beta\gamma}$, so that the signal region is defined in the plane given by those two masses. Then the background is evaluated from data by generating triplets of (β, $\beta\gamma$, p) in control regions defined inverting some of the cuts of the signal region and normalizing the corresponding distributions to the data events having low masses calculated with the two methods described above. Since no data is observed over the expected background, upper limits are set not only on the production of R-hadrons composed by gluino (see figure 7, right), but also on R-hadrons composed by bottom-squark and top-squark: gluino, bottom-squark and top-squark hadrons are excluded at 95% CL for masses below 1580 GeV, 805 GeV and 890 GeV, respectively.

The CMS Collaboration performed an analysis looking for charged massive long lived particles, such as R-hadrons, using 12.9 fb^{-1} from the 2016 data-taking [8]. The peculiar dE/dx and β variables are measured by CMS in the following ways:

- dE/dx is measured from the silicon tracker
- β is measured by the muon system, thanks to the fact that the DT and the CSC subdetectors can provide timing information for each hit

The analysis has been used to look for several signal hypotheses: R-hadrons (with gluino or top-squark), quasi stable leptons(tau-slepton), new massive Drell-Yan signal-like with charge 1 or 2 neutral under $SU(3)_C$ and $SU(2)_L$ ($|Q| = 1e, 2e$). Those new particles are looked for with two different approaches: requiring tracks to be reconstructed in both the silicon and in the muon subdetectors (tracker+TOF analysis); only requiring tracks in the silicon detectors (tracker-only analysis). The second approach is used to study possible signal hypotheses where the long lived particle can change the charge before the muon system and become neutral. Events are selected

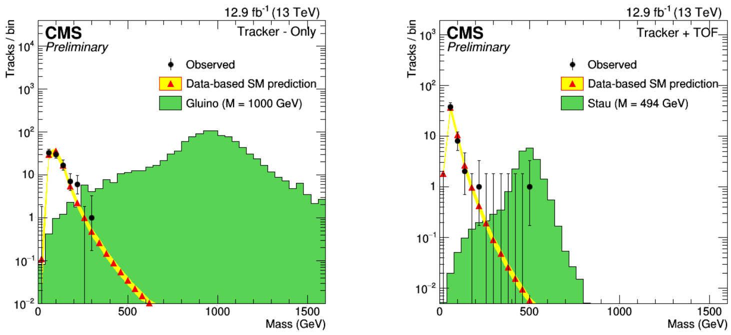

Figure 8 – Comparison between observation, predicted background and expected signal for the long lived particle candidate mass distribution for the tracker-only (left) or tracker+TOF (right) analyses [8].

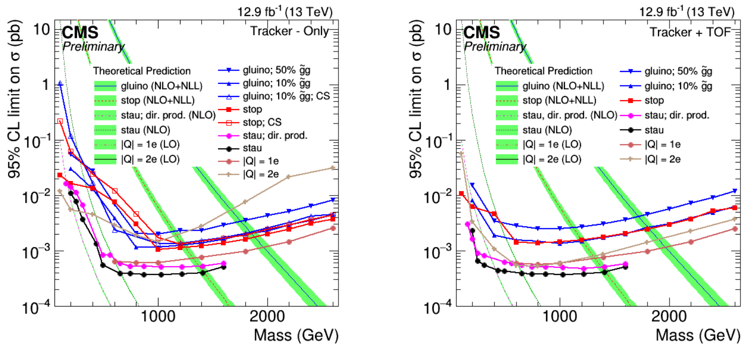

Figure 9 – Upper limits at 95% CL on production cross sections for various signal models for the tracker-only analysis (left) and tracker+TOF analysis (right) [8].

online by two different triggers that require the presence of a muon or the presence of high transverse missing energy, where this last trigger is used to recover the signals where the long lived particles is decaying before to reach the muon system. The offline selection is given by the presence of an isolated track with high p_T and passing several quality criteria. Then a minimum value of dE/dx and of $1/\beta$(only for tracker+TOF analysis) are required. The background is estimated from data by using the $ABCD$ method, i.e. by defining four data regions using two criteria (cut on the p_T of the track and cut on dE/dx): the number of expected background events in the signal region D is found with the formula BC/A, where B and C are the number of data events in the two regions defined by inverting only one of the two cuts, while A is the number of data events that fail both criteria. In figure 8, the expected background is compared with the observation in the signal region for the two tracker-only and tracker+TOF analyses for the final discriminating variable, i.e. the mass of the long lived candidate extrapolated from the dE/dx measurement. In the same figure also the distribution for a signal hypothesis is shown. Since no excess is observed over the expected background, we proceed with setting upper limits on the production cross section for the several signal hypotheses. In figure 9, observed upper limits at 95% CL on production cross sections for the various signal models for the tracker-only analysis and tracker+TOF analysis are shown: gluino (top-squark) R-hadrons are excluded for masses below 1850 (1250) GeV, tau-sleptons are excluded below 660/360 GeV (depending on the production mechanism) and finally DY signal-like with |Q|=1e (2e) are excluded for masses below 730 (890) GeV.

5 Conclusion

The ATLAS and the CMS Collaborations have been developed in the past years several strategies that look for new physics in an unconventional way. Those strategies have been presented in this talk. Between them, the two most recent model independent searches by ATLAS and CMS have been described. Those searches have been designed in order to reduce possible biases that are introduced when a particular phase space of a particular theory is studied, by analyzing the events only using a minimum set of requirements on the objects (leptons, jets, photons, etc.) reconstructions. Several hundreds of event classes are then defined by counting the reconstructed objects in each event and those classes are analyzed by looking for excesses or deficits of observation with respect to the background prediction. For both ATLAS and CMS, no significant deviations are found in data.

Then an analysis looking for black holes performed by the CMS Collaboration has been presented. The analysis is looking for excess of events in the S_T distribution, defined as the scalar sum of transverse energies of all the reconstructed objects in an event. The results have been interpreted in a model independent way, by setting limits on production cross section of possible signal hypotheses giving rise to high S_T and high object multiplicity; and in a model dependent

way, by looking for quantum and semiclassical black holes.
Finally the techniques developed by the ATLAS an the CMS Collaborations used to look for charged massive long lived particles have been presented, i.e. measurements of ionization energy loss, dE/dx, and of the speed of the particle, β, by using information coming from various subdetectors. Those measurements have been used to look for several possible signals that can predict a long lived particle that can go through all the detector.

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