PROCEEDINGS OF SCIENCE

PoS(CORFU2018)071

Exotics and BSM in ATLAS and CMS (non DM searches)

Piotr Zalewski[*][†]
National Centre for Nuclear Studies, Poland
E-mail: `Piotr.Zalewski@ncbj.gov.pl`

Search for new physics Beyond Standard Model (BSM) is one of the major goals of the ATLAS and the CMS experiments at the LHC. Search for phenomena other than motivated by mainstream supersymmetry is commonly referred to as exotica. Analyses directly related to search for dark matter particles was scheduled for other talks. What remains could be subdivided into searches for promptly decaying particles and for long lived once. Few representative examples of such analyses finished by ATLAS and CMS collaboration by the summer of 2018 are presented. No significant excess of signal event over predicted background was found in any analysis. More and more stringent exclusion limits are presented.

Corfu Summer Institute 2018 "School and Workshops on Elementary Particle Physics and Gravity" (CORFU2018)
31 August - 28 September, 2018
Corfu, Greece

---

[*] Speaker.

[†] Talk on behalf of the ATLAS and the CMS collaborations.

Introduction

Search for Beyond Standard Model (BSM) phenomena is one of the major goals of the ATLAS and the CMS experiments at the LHC. Significant part of en effort to respond to this challenge is coordinated within large *exotics* or *exotica* thematic subgroups of these collaborations. Exotica term was coined years before the start of the LHC to name BSM searches different from mainstream supersymmetry. Recently a search for dark matter (DM) becomes one of the most sound motivation for BSM searches at the LHC. However, analyses directly related DM searches was scheduled to be covered by other speakers at the conference. On the other hand almost each BSM model contains a DM particle candidate. It is in particular evident for scenarios with long lived particles (LLP) examples of which are presented in the Section 2.

1. Examples of searches for promptly decaying BSM particles

From analyses finished by the summer of 2018 the following were selected [1, 2, 3, 4, 5, 6, 7, 8] and presented at the conference. This list is shortened further to fit into this conference report. Two type of analyses are mentioned below.

Search for heavy $\tau\nu_\tau$ resonances in ATLAS and CMS

A search for heavy $\tau\nu_\tau$ resonances were performed by both ATLAS [1] and CMS [2] using 2016 data. In both cases Sequential Standard Model, in which W' is predicted to be produced at LHC and decay to $\tau\nu_\tau$, was used as a benchmark scenario. Missing transverse energy (momentum) was used for trigger and selection. Expected background was estimated using date if necessary or using MC simulation if possible and/or validated using data.

As the final search variable transverse mass

$$m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\tau}p_{\mathrm{T}}^{\mathrm{miss}}\left[1-\cos\Delta\phi\left(\vec{p}_{\mathrm{T}}^{\tau},\vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right)\right]}$$

was chosen by both experiments. Its distribution after final selection (points) together with estimated backgrounds (stacked histograms) and overlaid signal expectation lines are shown in the Figure 1 in the case of ATLAS analysis and in the Figure 2 for the CMS. No significant excess of data over background estimates were found. An example of cross-section times branching fraction upper limits are shown in the Figures 3 and 4 for the ATLAS and the CMS respectively. Expected W'_{SSM} is overlaid on both plots. In this benchmark model W' is excluded at 95% level up to masses well above about 3.5 TeV by both analyses separately.

Search for heavy $t\bar{t}$ resonances in ATLAS and CMS

A model independent search for new heavy particles that decay into top-quark pairs was performed by both ATLAS [3] and CMS [4] research teams.

The ATLAS analysis available in the summer of 2018 was based on events consistent with top-quark pair production selected by requiring a single isolated charged lepton, missing transverse momentum and jet activity compatible with a hadronic top-quark decay (lepton-plus-jets decay channel).

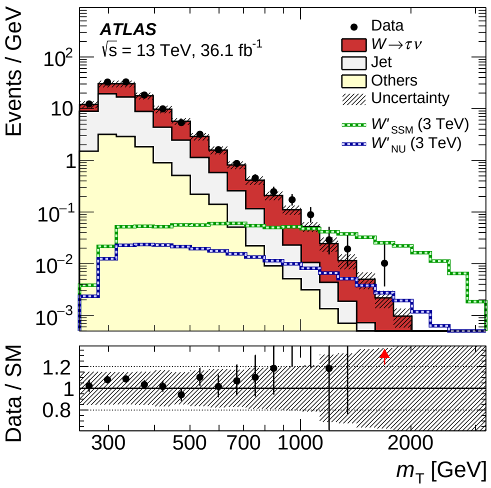

Figure 1: Transverse mass distribution after the event selection [1].

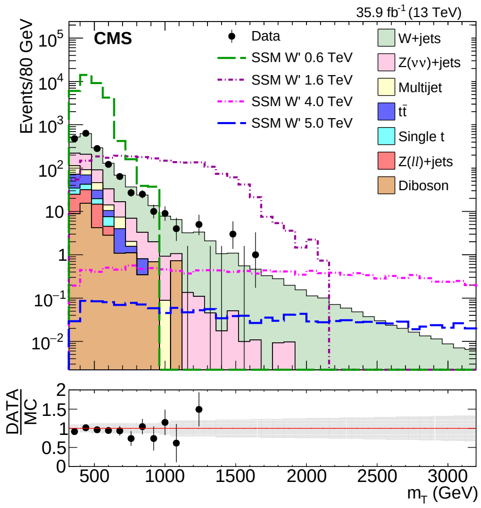

Figure 2: The m_T distribution after the final selection [2].

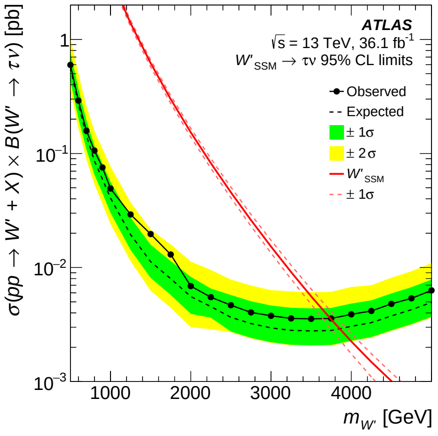

Figure 3: The 95% CL upper limit on the cross section times $\tau\nu$ branching fraction for W_{SSM} [1]. The W_{SSM} cross section is overlaid where the additional lines represent the total theoretical uncertainty.

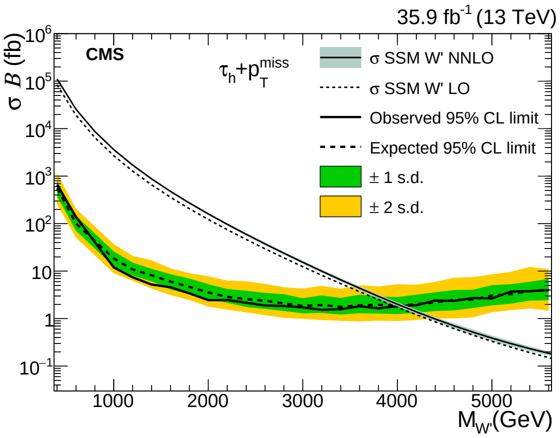

Figure 4: Expected (black dashed line) and observed (black solid line) 95% CL upper limits on the cross section for the production of W'_{SSM} boson [2]. The NNLO theoretical cross section with the corresponding PDF uncertainty band is also shown.

The CMS analysis considered three exclusive final states (single lepton, dilepton and fully hadronic channels) and used reconstruction techniques that are optimized for top quarks with high Lorentz boosts, which requires the use of non-isolated leptons and jet substructure techniques.

The main background in the search for heavy particles decaying into $t\bar{t}$ pair is non-resonant production of the same final state. This contribution was taken from MC simulation in both ATLAS ans CMS analyses, however data driven techniques were used to estimate multi-jet background.

No significant excess of events relative to the expected yield from standard model processes was observed. Estimated upper limits on the production cross section times branching fraction of Kaluza-Klein gluon decaying to a $t\bar{t}$ are shown in the Figures 5 and 6 for ATLAS and CMS analyses respectively.

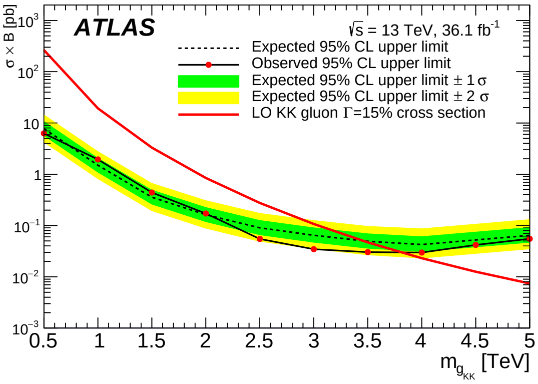

Figure 5: The observed and expected cross-section 95% CL upper limits on the g_{KK} signal for resonance widths of 15% [3]. The theoretical predictions for the production cross-section times branching ratio of $g_{\mathrm{KK}} \to t\bar{t}$ at the corresponding masses are also shown.

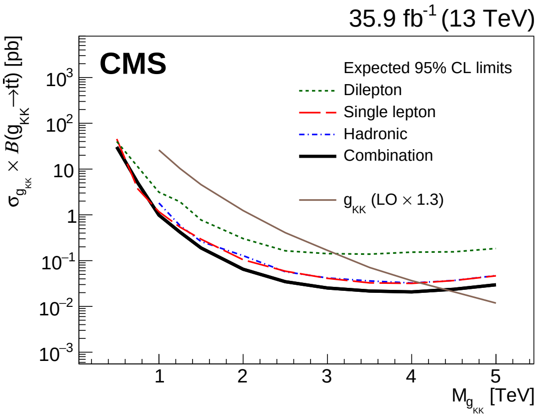

Figure 6: Comparison of the sensitivities for each analysis channel contributing to the combination [4]. The expected limits at 95% CL are shown for each channel with the narrow colored lines, while the combination result is shown with thick the black line.

2. Examples of searches for long lived particles

The list of presented at conference analyses is the following [9, 10, 11, 12, 13, 14]. Again only subset of them will be included below.

Search for displaced vertices in ATLAS and CMS

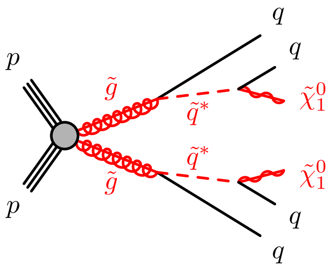

Figure 7: Diagram showing pair production of gluinos. (ATLAS [9]).

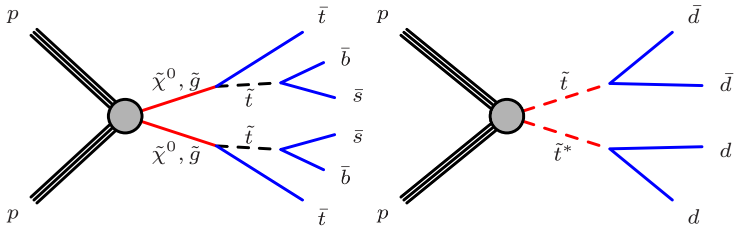

Figure 8: Diagrams for multi-jet (left) and dijet (right) benchmark models used in the displaced vertices search in CMS [10].

Searches for displaced vertices in data collected in the year 2016 were recently performed by both the ATLAS [9] and the CMS [10] experiments, but were targeted to different scenarios. In the case of ATLAS Split SUSY scenario was taken into account in which each long-lived gluino decays to quark and virtual squark which further decays to quark and neutralino (Fig. 7) giving two displaced vertices, jets and missing transverse energy. In the case of CMS models with RPV SUSY were taken as the motivation in which neutralino or gluino could be long-lived LSP giving multi-jet topology with two displaced vertices (Fig. 8 left) or stop could be long-lived LSP giving dijet topology also with two displaced vertices. RPV SUSY scenarios do not predict missing transverse energy.

In the ATLAS case tracks form displaced vertices were reconstructed using so called large-radius tracing in which additional tracks were formed from hits unused by standard track reconstruction. Displaced vertices found inside detector material were disregarded. Remaining background was estimated from data and the procedure was validated using data as well. Final search was performed using two dimensional distribution of estimated displaced vertex mass and number of associated tracks. No significant excess in the data with respect to predicted background was found what allowed to set upper limits on production cross section of considered in the analysis models (Fig.9).

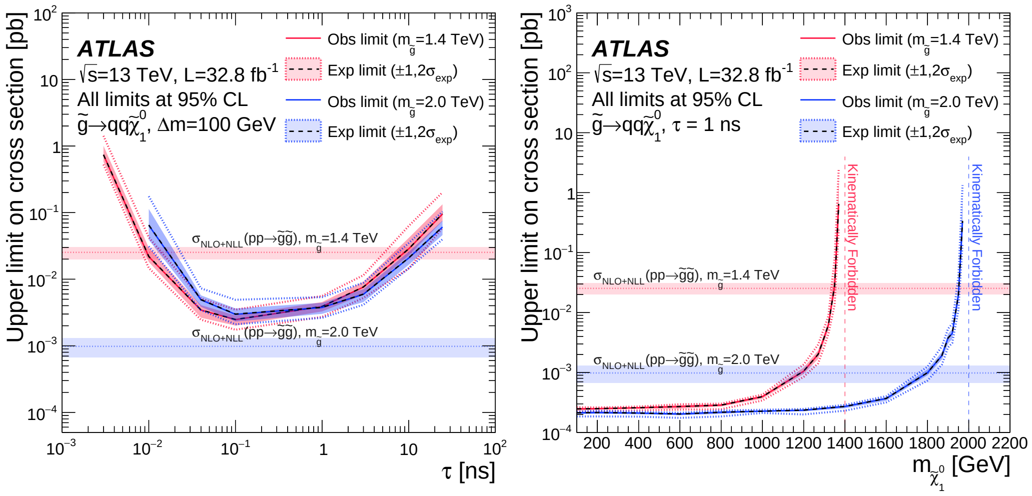

Figure 9: Upper 95% CL limits on the signal cross-section for two gluino mass points (1.4 and 2.0 TeV) in function of the lifetime τ for fixed gluino-neutralino mass difference of 100 GeV (left) and in function of the neutralino mass for fixed lifetime $\tau = 1$ ns (right) [9].

In the CMS case only displaced vertices inside beam pipe were considered. In the search two such vertices were required in each event. In the signal region not less than 5 tracks per vertex were required. Vertices with fewer number of tracks formed control region. Background templates were constructed using events with single vertex. Final search was performed using distance between displaced vertices. No significant excess in the data with respect to predicted background was found. Upper limits on cross-section times branching fraction squared are shown in the Figure 10. An instruction how the results could be interpreted in different models is attached and the end of the paper.

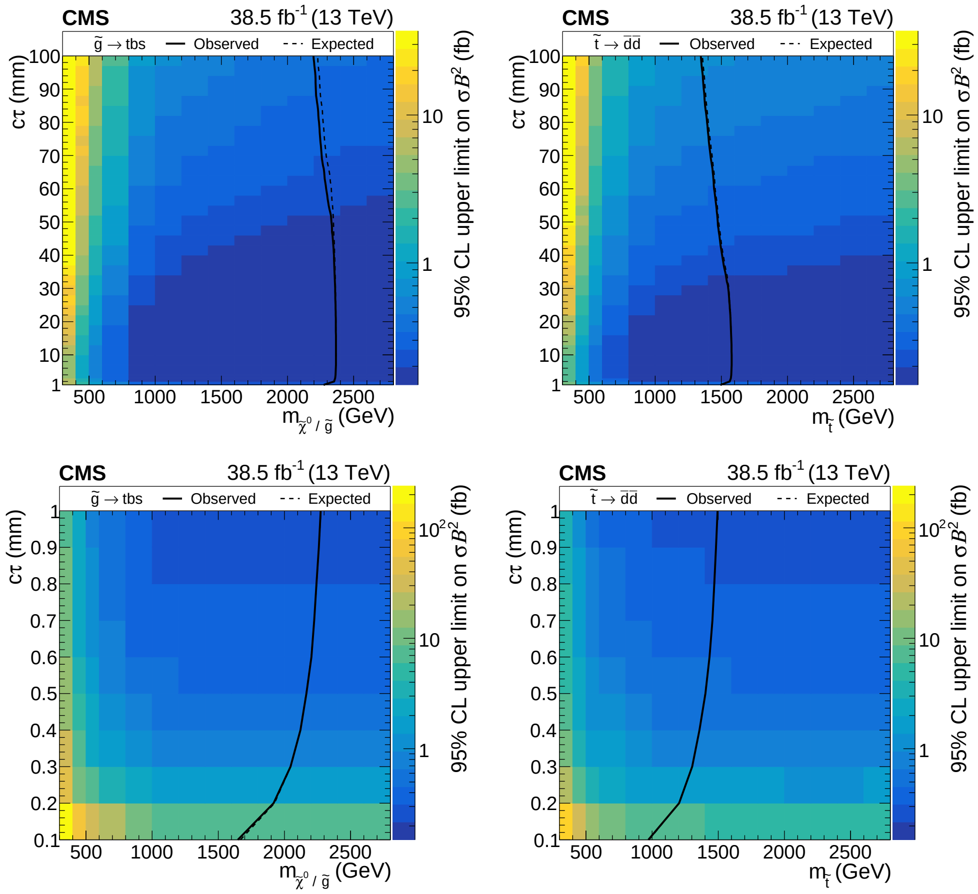

Figure 10: Observed 95% CL upper limits on σB^2 for multi-jet (left) and dijet (right) signals as a function of mass and $c\tau$ in the range 0.1–1 mm (lower plots), 1–100 mm (upper plots). Overlaid lines present exclusion for 100% branching fraction [10].

Search for heavy charged long-lived particles in ATLAS

This search [13] was performed using 2016 data and was based on specific ionization measurement in the ATLAS pixel detector. The dependence of dE/dx measurement on $\beta\gamma$ was parameterized using low momentum tracks (Fig. 11).

Table 1: Summary of the different selection requirements applied to the signal region (SR), the validation region (VR), and the control regions (CR) in the ATLAS search for heavy charged long-lived particles [13].

	SR	VR	p-CR		dE/dx-CR	
			for SR	for VR	for SR	for VR
Track Momentum [GeV]	>150	50–150	>150	50–150	>150	50–150
E_T^{miss} [GeV]	>170		>170		<170	
Ionisation [MeV g^{-1} cm^2]	> 1.8		< 1.8		–	

Two signal selection used were named stable and metastable. The main distinction was muon veto for the metastable one. Events were triggered using E_T^{miss}. Irreducible background due to

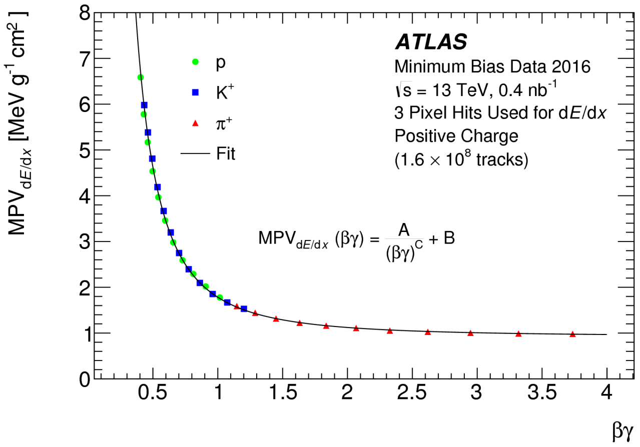

Figure 11: Illustration of the parameterization of pixel dE/dx dependence on $\beta\gamma$ using low momentum tracks [13].

multiple accidental high dE/dx measurements (Landau tail) unnoticed track overlap etc. were estimated from data. Selection criteria for the signal region (SR), the validation region (VR) and control regions (CR) are given in the Table 1.

The validation and the final search (Fig. 12) was done using mass estimate $m = p/(\beta\gamma)$ obtained as a numeric solution of the parameterization shown in the Figure 11.

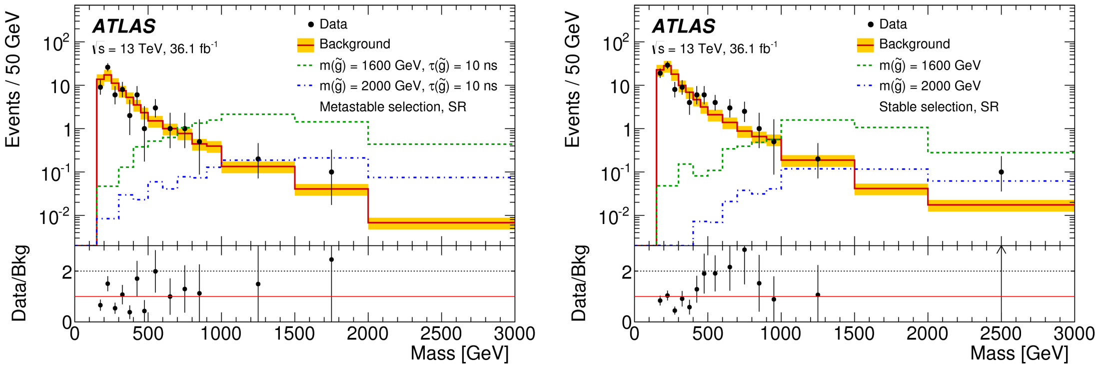

Figure 12: The reconstructed candidate track mass distributions for observed data, predicted background, and the expected contribution from two signal models in the (left) metastable and (right) stable R-hadron signal regions. The yellow band around the background estimation includes both the statistical and systematic uncertainties [13].

The number of candidates was found to be consistent with the background expectation and model-independent 95% CL on the visible cross-section was calculated. Interpretation of these limits in the gluino lifetime–mass plane is shown in the Figure 13 in comparison to the results from previous ATLAS publications.

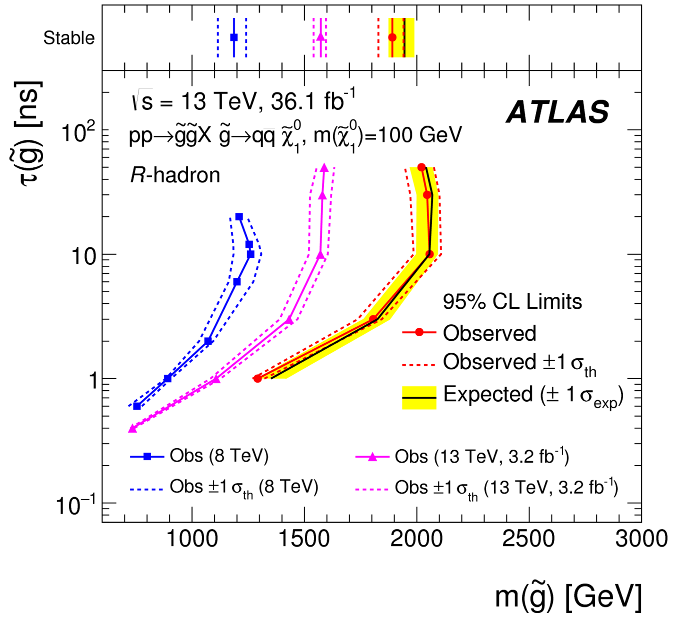

Figure 13: Observed and expected 95% lower limits on the gluino mass in the gluino lifetime–mass plane [13].

Search for emerging jets in CMS

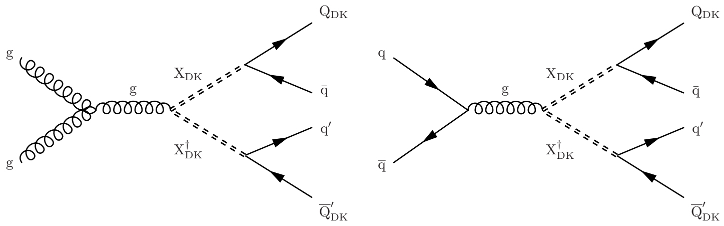

Figure 14: Diagrams for pair production of mediator particles (CMS [14]).

A search for new type of topology was performed by CMS [14]. Within so called dark QCD model pair of mediator particles X_{DK} (charged under both the new dark force and under SM QCD) could be produced. Each mediator decay promptly to a quark and a dark quark Q_{DK} pair (Fig. 14). Each dark quark dark hadronize into long-lived dark pions π_{DK} which decay (via mediator) to SM hadrons. In the final state four hard jets are expected, but two of them emerge gradually as dark pions decays. Such emerging jet contains significant fraction of non-pointing constituents. Distributions of two variables used to distinguish these jets form background for different combinations of dark mediator mass, dark pion mass and lifetime are shown in the Figure 15.

Misidentification probability was measured in function of jet multiplicity using events triggered by hard photon instead of large scalar sum of jets transverse momenta. Significant difference

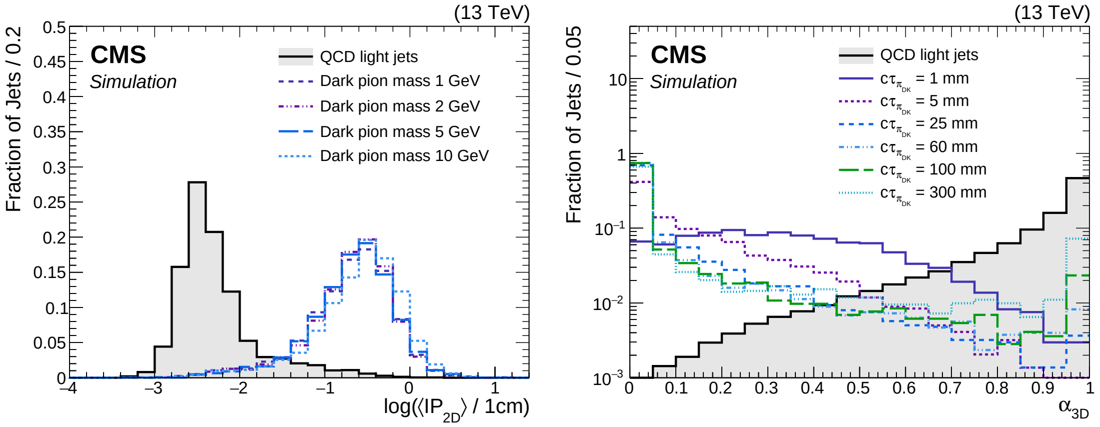

Figure 15: Distributions of: a median $\langle \mathrm{IP}_{2\mathrm{D}} \rangle$ of 2D impact parameter for 1 TeV mediator and dark pion $c\tau = 25$ mm (left) and fraction $\alpha_{3\mathrm{D}}$ of jet transverse momentum due to pointing jet constituents for 1 TeV mediator and 5 GeV dark pion (right) [14].

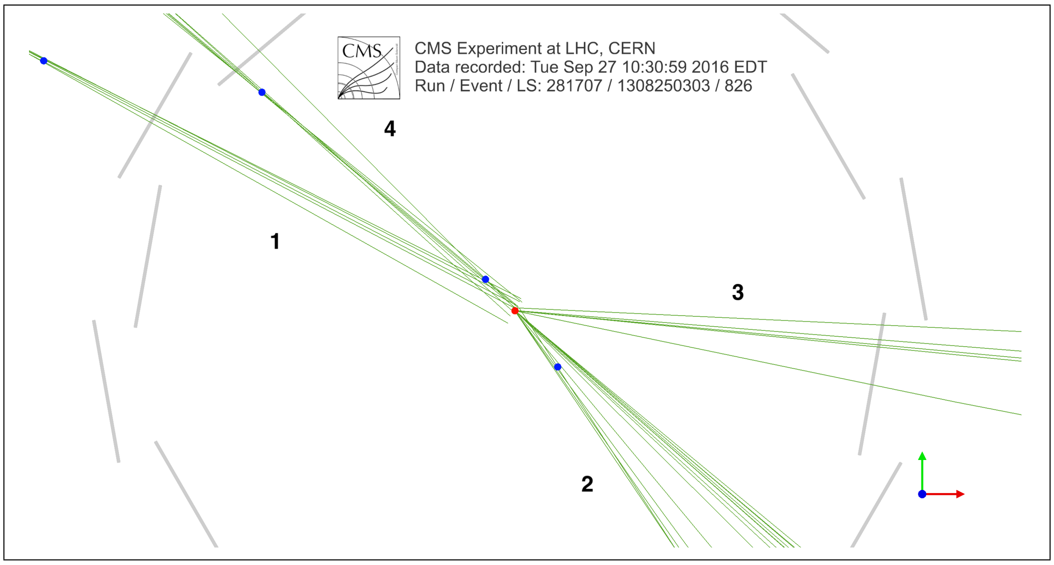

Figure 16: A display of a signal candidate event. Jets 1 and 4 passed emerging jet criteria. The part of the detector shown is the innermost silicon pixel layer [14].

between b-quark and non-b-quark jets were carefully taken into account. The procedure were verified on simulated samples and validated using QCD enhanced data.

In the Figure 16 a display of one candidate is shown.

No significant excess of event above predicted background was observed and 95% CL limits on cross section in function of mediator mass as well as dark pion mass and its lifetime were set. Graphical presentation of such exclusions for dark pion mass of 5 GeV are shown in the Figure 17.

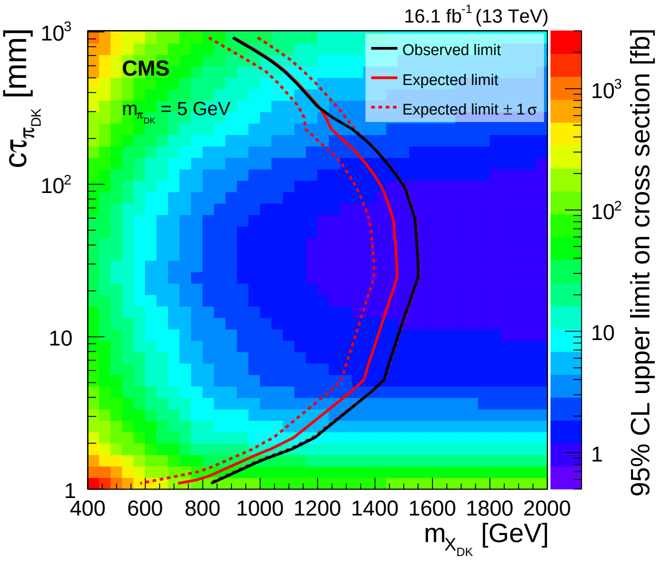

Figure 17: Upper limits at 95% CL on the signal cross section and signal exclusion contours [14].

Summary

By summer of the year 2018 majority of developed searches for BSM phenomena based on more than 30 fb^{-1} of proton-proton data registered at $\sqrt{s} = 13$ TeV by the ATLAS and the CMS separately were finished. No new physics were found. It means that if Nature is still hiding something new in the vicinity of TeV it is not so easy to be uncovered. One possibility is that it is more exotic that we expected. We have another dozens of inverse femtobarns taken in 2017 and 2018 as well as run3 and high luminosity run of the LHC. Our analyses are improving more and more. Completely new ideas are developed. We will keep searching.

Acknowledgments

I would like to thank the organizers of the conference for exceptional hospitality as well as the ATLAS and the CMS conference committees for allowing me to speak on behalf of these collaborations. This work was supported in part by NCN grant 2014/039982014/15/B/ST2/03998.

References

[1] The ATLAS collaboration, *Search for High-Mass Resonances Decaying to $\tau\nu$ in pp Collisions at $\sqrt{s}$=13 TeV with the ATLAS Detector*,
Phys. Rev. Lett. **120**(2018)161802, doi:10.1103/PhysRevLett.120.161802, arXiv:1801.06992

[2] The CMS collaboration, *Search for a W' boson decaying to a τ lepton and a neutrino in proton-proton collisions at $\sqrt{s} = 13$ TeV*,
Phys. Lett. **B792**(2019)107-131, doi:10.1016/j.physletb.2019.01.069, arXiv:1807.11421

[3] The ATLAS collaboration, *Search for heavy particles decaying into top-quark pairs using lepton-plus-jets events in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*,

Eur. Phys. J. **C78**(2018)565, doi:10.1140/epjc/s10052-018-5995-6, arXiv:1804.10823

[4] The CMS collaboration, *Search for resonant* $\mathrm{t\bar{t}}$ *production in proton-proton collisions at* $\sqrt{s} = 13$ TeV, JHEP **04**(2019)031, doi:10.1007/JHEP04(2019)031, arXiv:1810.05905

[5] The ATLAS collaboration, *Combination of searches for heavy resonances decaying into bosonic and leptonic final states using 36 fb*$^{-1}$ *of proton-proton collision data at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, Phys. Rev. **D98**(2018)052008, doi:10.1103/PhysRevD.98.052008, arXiv:1808.02380

[6] The ATLAS collaboration, *Combination of the searches for pair-produced vector-like partners of the third-generation quarks at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, Phys. Rev. Lett. **121**(2018)211801, doi:10.1103/PhysRevLett.121.211801, arXiv:1808.02343

[7] CMS Collaboration, *Search for a heavy resonance decaying to a top quark and a vector-like top quark in the lepton+jets final state*, CMS-PAS-B2G-17-015

[8] The CMS collaboration, *Search for a W' boson decaying to a vector-like quark and a top or bottom quark in the all-jets final state*, CMS-PAS-B2G-18-001

[9] The ATLAS collaboration, *Search for long-lived, massive particles in events with displaced vertices and missing transverse momentum in* $\sqrt{s} = 13$ *TeV pp collisions with the ATLAS detector*", Phys. Rev. **D97**(2018)052012", doi:10.1103/PhysRevD.97.052012, arXiv:1710.04901

[10] The CMS collaboration, *Search for long-lived particles with displaced vertices in multijet events in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*, Phys. Rev. **D98**(2018)092011, doi:10.1103/PhysRevD.98.092011, arXiv:1808.03078

[11] The ATLAS collaboration, *Search for long-lived particles in final states with displaced dimuon vertices in pp collisions at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, Phys. Rev. **D99**(2019)012001, doi:10.1103/PhysRevD.99.012001, arXiv:1808.03057

[12] The CMS collaboration, *Search for decays of stopped exotic long-lived particles produced in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*, JHEP **05**(2018)127, doi:10.1007/JHEP05(2018)127, arXiv:1801.00359

[13] The ATLAS collaboration, *Search for heavy charged long-lived particles in proton-proton collisions at* $\sqrt{s} = 13$ *TeV using an ionisation measurement with the ATLAS detector*, Phys. Lett. **B788**(2019)96-116, doi:10.1016/j.physletb.2018.10.055, arXiv:1808.04095

[14] The CMS Collaboration, *Search for new particles decaying to a jet and an emerging jet*, JHEP **02**(2019)179, doi:10.1007/JHEP02(2019)179, arXiv:1810.10069