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Prospects for BSM searches at the high-luminosity LHC with the CMS detector

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Abstract

After a series of upgrades the Large Hadron Collider will deliver an integrated luminosity of up to 3000 fb^{-1} with $\sqrt{s}$ = 14 GeV for each experiment. Aspects of the supersymmetry and other beyond the standard model (BSM) search programme are discussed for this scenario. These include the expected discovery reach for gluinos decaying to third generation squarks as well as to light squarks, for the third generation squark decaying to top quarks and neutralino and for the neutralino-chargino pairs decaying to final states including a Z and a W boson. Depending on the SUSY particles, the discovery reach can be improved by about 300 to 400 GeV with increasing the luminosity from 300 to 3000 fb^{-1}. The potential for discovery of non-SUSY new particles is also discussed.

Keywords: HL-LHC, CMS, SUSY, BSM

1. Introduction

Several years of LHC operation lead to a remarkable success of the standard model (SM) culminating in the discovery of a Higgs boson. Nonetheless, there are still unanswered fundamental questions in nature which include non observation of a dark matter (DM) candidate, origin of neutrino masses, matter-antimatter imbalance in the universe, etc. Various theoretical constructions, which compete to provide an explanation for these phenomena, are extensively tested at the LHC. No indication for non-SM processes is observed and allowed phase-space for new models is severely constrained. The new energy and intensity frontier opening up in the next years allows to further explore the uncharted territory and to study the newly discovered particles.

One of the most popular extensions to the SM is the supersymmetry (SUSY) which in the R-parity conserving context naturally provides a DM candidate as a lightest supersymmetric particle (LSP). Often the LSP is the lightest neutrino which is produced via electroweak or vector-boson-fusion (VBF) processes. This implies that the production cross section is very low and therefore it is necessary to collect large amount of data to provide conclusive results. Apart from light neutralinos, the so called natural SUSY scenarios favour existence of not too heavy 3$^{\mathrm{rd}}$ generation squarks and gluinos which are necessary to stabilise Higgs boson mass at the level of one- and two-loops quantum corrections. The discovery reach for several benchmark scenarios for these new particles are considered for both 300 and 3000 fb^{-1}.

Several non-SUSY models for new physics are also considered, including production of additional heavy gauge bosons, heavy stable charged particles and others.

2. CMS detector upgrade

The upgrade timeline of the LHC and the CMS detector [1] is structured to provide a gradual increase in center-of-mass energy and collected integrated luminosity. in 2014, the LHC is finishing its first long shutdown (LS1) and preparing for running at $\sqrt{s}$ = 13 TeV in 2015. The goal is to collect 300 fb^{-1} of pp data by the end of 2021.

A second long shutdown (LS2) in 2018 is needed to upgrade the detectors for operating at double the design luminosity and an average pile-up of 50 ("Phase I" upgrade). The following phase of planned LHC operation,

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the High Luminosity LHC (HL-LHC), will start with the third long shutdown (LS3) between 2022 and 2023. During this period the LHC machine and detectors will be upgraded to allow for luminosity of 5×10^{34} cm^{-2}s^{-1} and an average pile-up of 128, with the goal of accumulating 3000 fb^{-1} ("Phase II" upgrade).

A configuration assumed for the Phase II upgrade studies includes replaced electromagnetic endocarp calorimeter, increase of ϕ segmentation in the hadronic endcap calorimeter, upgraded tracker and extended muon system [2].

3. SUSY searches

The projections for several representative searches for SUSY by CMS [3, 4, 5, 6, 7] are performed in two scopes. Discovery reach at 300 fb^{-1} is estimated based on the analyses designed for 8 TeV conditions and using 8 TeV Monte Carlo samples by scaling the luminosity and cross section values and without dedicated selection optimisation [8]. Two scenarios are considered: in conservative scenario ("Scenario A"), the signal and background yields, and the uncertainty on the background, are scaled by the ratio of the luminosities (20 fb^{-1} for 8 TeV and 300 fb^{-1} for 14 TeV) and by the ratio of the cross sections for signal and background (σ_{sig} and σ_{bkg}):

$$R_{\text{sig(bkg)}} = \frac{300\,\text{fb}^{-1}}{20\,\text{fb}^{-1}} \times \frac{\sigma_{\text{sig(bkg)}}(14\,\text{TeV})}{\sigma_{\text{sig(bkg)}}(8\,\text{TeV})}. \quad (1)$$

In more optimistic scenario ("Scenario B"), relative uncertainty on the background is reduced assuming background estimation methods are reoptimized and profit from the large amount of collected data to study and describe SM processes.

Further discovery reach at 3000 fb^{-1} is studied with the upgraded CMS detector configuration [2]. A dedicated analysis reoptimization is performed to take advantage of new detector performance and to take into account new conditions more accurately.

The processes described here include gluino-pair production (with $\tilde{g} \to q\bar{q}\tilde{\chi}^0_1$ or $\tilde{g} \to t\bar{t}\tilde{\chi}^0_1$), stop-pair production (with $\tilde{t}_1 \to t\tilde{\chi}^0_1$), chargino-neutralino pair production with WZ or WH bosons in final states. The production cross sections are computed with at the next-to-leading-order accuracy with Prospino2 (Fig. 1).

3.1. Top squark

The discovery reach is extrapolated from the single-lepton search performed at 8 TeV [5]. In Scenario A, the signal and background yields are scaled according

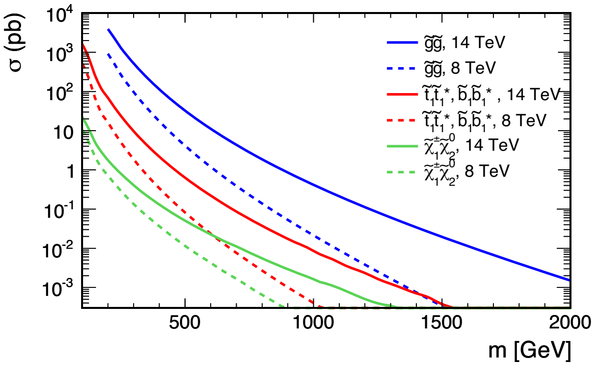

Figure 1: Next-to-leading order production cross sections for SUSY particles.

to Eq. 1, leaving the size of relative uncertainties unchanged. The signal production cross section increases by a factor of 4 to 20 for top squark masses from 200 to 1000 GeV, while the main background ($t\bar{t}$) cross section grows by a factor of 3.3. In Scenario B it is assumed in addition that uncertainty on the background is reduced by $1/\sqrt{R_{\text{bkg}}}$, but at the same time it remains not smaller than 10%. The comparison of discovery reach at 8 TeV and 14 TeV in two scenarios is shown in Fig. 2. With 300 fb^{-1} a discovery is possible up to masses of top squark of 750–950 GeV and an LSP masses of 300–450 GeV.

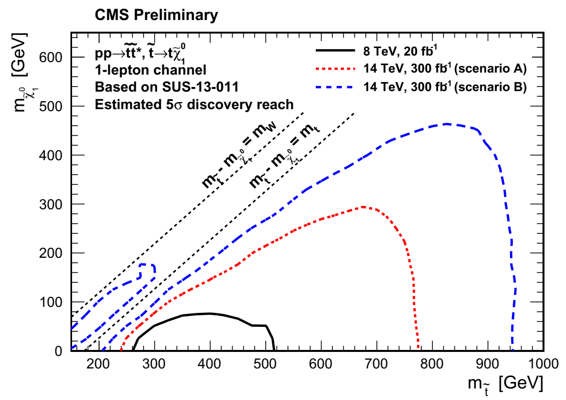

Figure 2: 5σ discovery reaches for direct stop-pair production where each top squark decays to a top quark and an LSP.

3.2. Gluino

Estimation of the discovery potential for the process of gluino-pair production decaying to four jets and two LSPs is done with reoptimization of the search exploiting large number of jets (N_{jets}), hadronic activity (H_T =

$\sum_{\text{jets}} p_T$ for jets with $p_T > 50$ GeV and $|\eta| < 2.5$) and missing hadronic transverse energy ($\not{H}_T = |-\sum_{\text{jets}} \vec{p}_T|$ for jets with $p_T > 30$ GeV and $|\eta| < 5.0$) to discriminate between signal and background [9]. Main SM backgrounds to this search are $Z(\nu\bar{\nu})$+jets events and $W(\ell\nu)$+jets events from W boson production or $t\bar{t}$ processes, where the e or μ escapes detection or a τ decays hadronically. Other processes including QCD multijet events have negligible contribution when moving to higher values of $\not{H}_T$. Five search regions are defined to provide the best sensitivity for various spectra of gluino and LSP masses [2]. High values of required N_{jets}, H_T and $\not{H}_T$ ensure that the analysis is not sensitive to the increased amount of pileup interactions. The discovery reach at 300 and 3000 fb^{-1} is shown in Fig. 3. Discovery of gluinos is feasible up to ~2.2(1.8) TeV with LSP masses up to ~ 500(400) GeV at 14 TeV with an integrated luminosity of 3000(300) fb^{-1}.

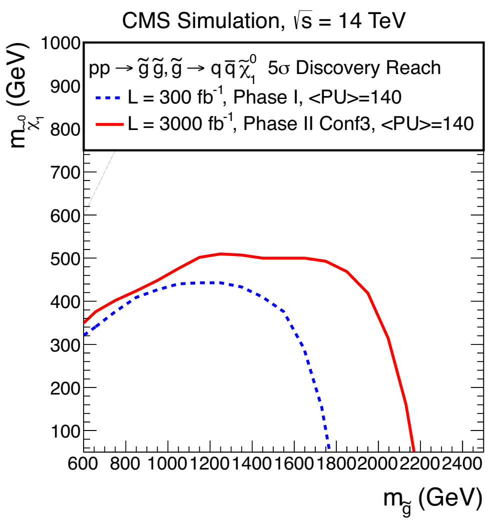

Figure 3: The projected 5σ discovery reaches for gluino-pair production yielding four light quarks and two LSPs.

In case gluinos decay to top quarks and an LSP, the most sensitive search is the one using single lepton with multiple (b) jets in the final state [4]. Main SM backgrounds comprise $t\bar{t}$, $t\bar{t}$+W/Z and W/Z + jets events, where lepton and missing transverse energy (E_T^{miss}) come from the W→ $\ell\nu$ process or a leptonic decay of a Z boson where one of the leptons is not detected. The search strategy explores this fact relying on an angle between a reconstructed W boson candidate and a lepton: $\Delta\phi(W,\ell)$ assumes large values for signal processes while peaking near zero for SM backgrounds. Eight search regions binned in b jet multiplicity and $S_T^{\text{lep}} = p_T^{\ell} + E_T^{\text{miss}}$ are defined and require at least 3 b jets and $S_T > 450$ GeV. It is found that the analysis is robust against increased pile up (as shown in Fig. 4). It is estimated that the discovery of gluinos with masses up to 2.2(1.9) TeV for LSP masses of 1.2(1.0) TeV is possible with 3000(300) fb^{-1}.

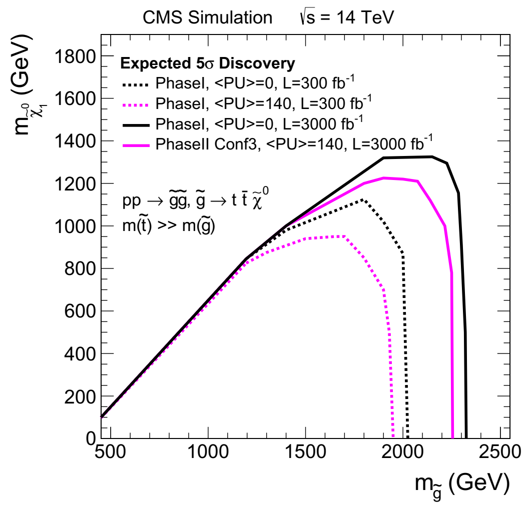

Figure 4: The projected 5σ discovery reaches for gluino-pair production yielding four top quarks and two LSPs.

3.3. Electroweakly produced SUSY

Searches for the direct electroweak production of SUSY particles profit the most from HL-LHC operation due to the low production cross sections of these processes. The estimation of future discovery reach is performed based on a three-lepton search for chargino-neutralino pair production decaying to W and Z bosons and two LSPs carried out at 8 TeV [7]. Main backgrounds for this search arise from the SM WZ production, $t\bar{t}$+ Z process and multi boson production. To efficiently mitigate the background, search regions asymmetrically binned in E_T^{miss} and M_T are constructed (M_T is a transverse mass of a lepton not forming a Z candidate and missing transverse energy). The search regions with intermediate values of M_T and E_T^{miss} are the most affected by the high pile-up environment leading to decreased sensitivity at low mass splittings between chargino and an LSP (Fig. 5). The analysis is sensitive to chargino and neutralino masses up to 700(500) GeV with LSP masses up to 200(150) GeV at integrated luminosity of 3000(300) fb^{-1}. The impact of the decreased branching fraction to a WZ final state is shown in Fig. 6. The discovery reach diminishes significantly to 400(200) GeV for LSP masses of 50(20) GeV with 3000(300) fb^{-1}.

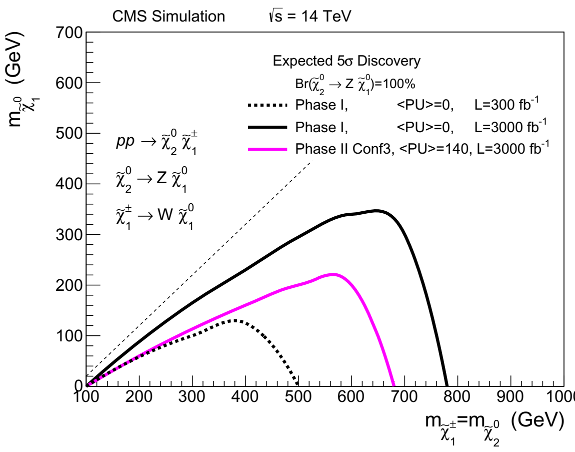

Figure 5: The projected 5σ discovery reaches for chargino-neutralino pair production decaying to W and Z bosons and two LSPs.

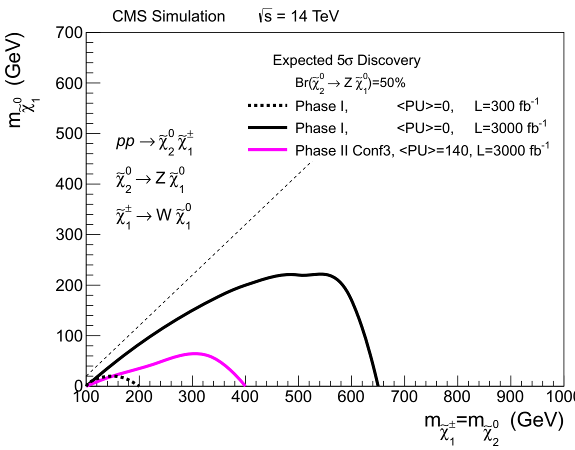

Figure 6: The projected 5σ discovery reaches for chargino-neutralino pair production decaying to W and Z bosons and two LSPs with BF = 50%.

4. Exotic new particles

Discovery reach for several non-SUSY new physics scenarios is estimated as well. The considered models include searches for heavy stable charged particles, additional gauge bosons (Z′ and W′), dark matter in monolepton channel and vector-like top partners.

4.1. Heavy stable charged particles

Extrapolation is performed based on the results of 7 and 8 TeV search [10]. The key features of the new processes exploited in the analysis are long time-of-flight (TOF) to the outer muon system and anomalously large energy deposition in the inner tracker. Unlike previous searches described here, where backgrounds were due to the SM model processes with similar signatures, the background in this case arises mainly from the instrumental effects. Hence the backgrounds scale linearly with integrated luminosity, and signal to background ratio remains unchanged. The adjustment for the signal acceptance is made to take into account reduced trigger-time window due to smaller LHC bunch spacing (25 ns as opposed to 50 ns), the new value being obtained from the full 8 TeV Monte Carlo simulation. The results are presented for two scenarios: using only TOF information in case no dE/dx measurement is available after CMS tracker upgrade, and using both TOF and dE/dx information in case it is possible to preserve dE/dx information. Figure 7 shows the estimation of production cross section yielding 5σ excess in two scenarios for $3000(300)\,\mathrm{fb}^{-1}$ in case of inclusive production of lepton-like staus [8].

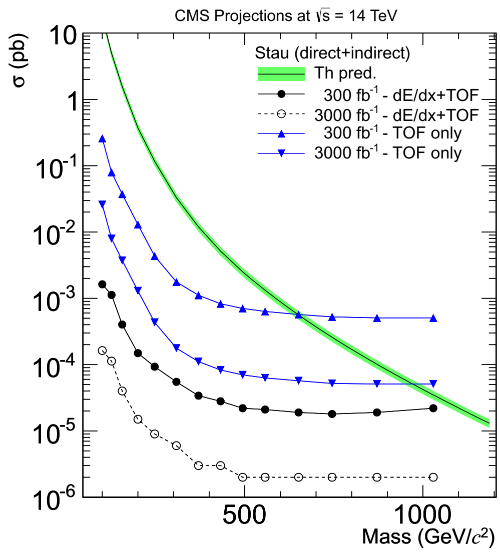

Figure 7: Minimum cross sections for an expected signal significance of 5σ for direct and indirect production of staus in the context of GMSB.

4.2. Additional gauge bosons

Search for additional heavy gauge bosons is extrapolated based on 7 and 8 TeV analysis [11]. An unchanged lepton acceptance is assumed, and at the same time the possible degradation of lepton measurement is taken into account, such as worse muon p_{T} resolution and worse electron resolution and saturation effects in the calorimeter. A pessimistic scenario in which the reconstruction in barrel ECAL is not possible is also shown. Main SM background is high-mass Drell-Yan production of lepton pairs, the background from $t\bar{t}$ process self-vetoes since leptons are not isolated in boosted top events. Other SM processes yield a (sub) percent contribution. The discovery reach in the electron channel for various Z′ models is shown in Fig. 8. Similar performance is found in the muon channel.

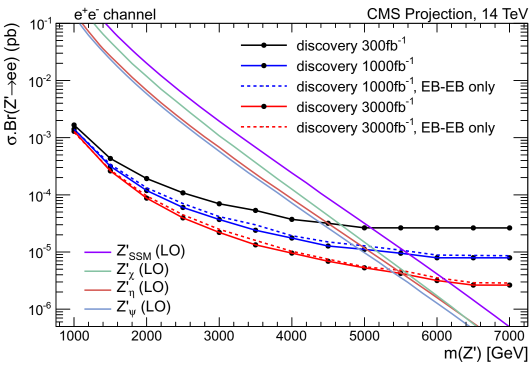

Figure 8: Minimum cross sections times branching ratio for an expected signal significance of 5σ in the dielectron channel for various luminosity scenarios. "EB-EB only" lines correspond to the reduced acceptance scenario in which electrons are reconstructed in the ECAL barrel only.

4.3. Monoleptons+$E_{\mathrm{T}}^{\mathrm{miss}}$

The extrapolation of the high-p_{T} lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ search for the HL-LHC is performed in the context of two new physics models: the SSM W′ boson decaying with 8% BF into each lepton flavour, and a dark matter effective theory where a pair of new particles is produced in association with a lepton and a neutrino.

Estimation of the discovery reach is based on the 8 TeV analysis [12]. Signal acceptance is assumed to be unchanged as well as lepton isolation and efficiency. The main source of background is high transverse mass tail of the W→ $\ell\nu$ process, other SM processes giving no contribution. The W′ boson with mass up to 6 TeV can be discovered when combining electron and muon channels.

The discovery reach in the dark matter-nucleon cross section in cases of vector or axial-vector type couplings is shown in Fig. 9.

4.4. Heavy vector-like charge 2/3 quarks

Introduction of vector-like quarks helps to solve hierarchy problem by cancelling diverging contributions of top quark to the Higgs boson mass. A search in three decay channels (bW, tZ and tH) with eight final states is performed at 8 TeV [13], and its results are considered to estimate discovery potential at the HL-LHC [8, 14].

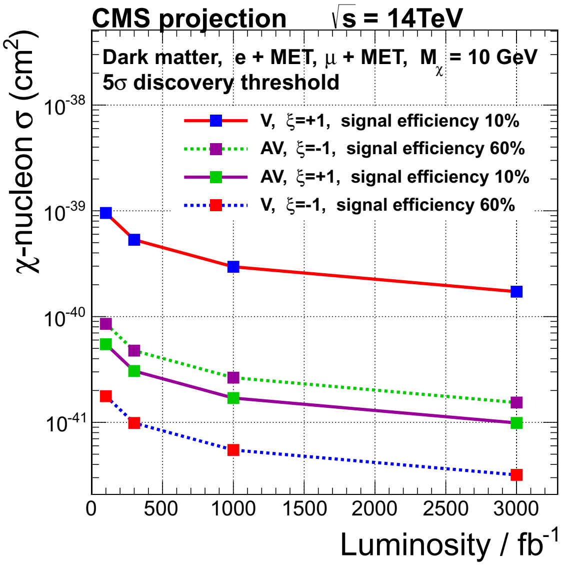

Figure 9: Minimum dark matter-nucleon cross section for an expected signal significance of 5σ for the pair-produced dark-matter in various luminosity scenarios.

The signal and background yields are scaled with the respective cross section values, and a conservative background uncertainties are applied. It is expected that the final sensitivity does not depend strongly on the exact branching ratios of T quarks. Figure 10 shows the estimated discovery cross section for various T quark masses in several luminosity scenarios, with the discovery potential reaching 1.2 TeV with 3000 fb^{-1} of pp data.

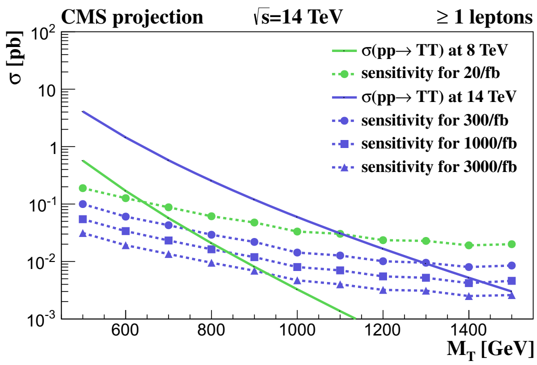

Figure 10: Minimum dark matter-nucleon cross section for an expected signal significance of 5σ for the pair-produced dark-matter in various luminosity scenarios.

5. Conclusions

CMS detector demonstrated an excellent performance during the LHC Run I which lead to a discovery of a Higgs boson and showed sensitivity over wide range of signatures. Though no physics beyond the SM has been observed yet, but in many cases we just started to test various BSM theories. It was demonstrated that new (HL)-LHC era allows to significantly push the current boundaries and open a window to not probed before mass ranges of new particles. Moreover, presented projections conservatively relied on the 8 TeV performance and allow for new developments to widen the horizon further.

References

[1] CMS Collaboration, The CMS experiment at the CERN LHC, JINST 3 (2008) S08004.

[2] CMS Collaboration, Study of the discovery reach in searches for supersymmetry at CMS with 3000 fb^{-1}, CMS Physics Analysis Summary CMS-PAS-FTR-13-014 (2013).

[3] CMS Collaboration, Search for gluino mediated bottom- and top-squark production in multijet final states in pp collisions at 8 TeV, Phys. Lett. B 725 (2013) 243. arXiv:1305.2390, doi:10.1016/j.physletb.2013.06.058.

[4] CMS Collaboration, Search for supersymmetry in pp collisions at $\sqrt{s}$ = 8 TeV in events with a single lepton, large jet multiplicity, and multiple b jets, Phys. Let. B 733 (2014) 328. arXiv:1311.4937, doi:10.1016/j.physletb.2014.04.023.

[5] CMS Collaboration, Search for top-squark pair production in the single-lepton final state in pp collisions at $\sqrt{s}$ = 8 TeV, Eur. Phys. J. C 73 (2013) 2677. arXiv:1308.1586, doi:10.1140/epjc/s10052-013-2677-2.

[6] CMS Collaboration, Search for new physics in events with same-sign dileptons and jets in pp collisions at $\sqrt{s}$ = 8 TeV, JHEP 01 (2014) 163. arXiv:1311.6736, doi:10.1007/JHEP01(2014)163.

[7] CMS Collaboration, Searches for electroweak production of charginos, neutralinos, and sleptons decaying to leptons and W, Z, and Higgs bosons in pp collisions at 8 TeV, Eur. Phys. J. C 74 (2014) 3036. arXiv:arXiv:1405.7570, doi:10.1140/epjc/s10052-014-3036-7.

[8] CMS Collaboration, Projected performance of an upgraded CMS detector at the LHC and HL-LHC: Contribution to the Snowmass Process, Tech. rep. (2013). arXiv:1307.7135.

[9] CMS Collaboration, Search for new physics in the multijet and missing transverse momentum final state in proton-proton collisions at $\sqrt{s}$ = 8 TeV, JHEP 06 (2014) 055. arXiv:1402.4770, doi:10.1007/JHEP06(2014)055.

[10] CMS Collaboration, Searches for long-lived charged particles in pp collisions at $\sqrt{s}$ = 7 and 8 TeV, JHEP 07 (2013) 122. arXiv:1305.0491, doi:10.1007/JHEP07(2013)122.

[11] CMS Collaboration, Search for heavy narrow dilepton resonances in pp collisions at $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 8 TeV, Phys. Lett. B 720 (2013) 63. arXiv:1212.6175, doi:10.1016/j.physletb.2013.02.003.

[12] CMS Collaboration, Search for physics beyond the standard model in final states with a lepton and missing transverse energy in proton-proton collisions at $\sqrt{s}$ = 8 TeV, submitted to Phys. Rev. D (2014). arXiv:1408.2745.

[13] CMS Collaboration, Inclusive search for a vector-like T quark with charge 2/3 in pp collisions at $\sqrt{s}$ = 8 TeV, Phys. Lett. B 729 (2014) 149. arXiv:1311.7667, doi:10.1016/j.physletb.2014.01.006.

[14] CMS Collaboration, Sensitivity study of the prospects for searching for heavy vector-like charge 2/3 quarks at 14 TeV with the upgraded CMS detector, CMS Physics Analysis Summary CMS-PAS-FTR-13-026 (2013).