IL NUOVO CIMENTO **39 C** (2016) 347
DOI 10.1393/ncc/i2016-16347-1

Colloquia: La Thuile 2016

New physics in final states with jets or vector bosons

A. L. Cunrath Pequegnot on behalf of the CMS Collaboration
IPNL, Institut de Physique Nuclaire de Lyon - Lyon, France

received 26 July 2016

Summary. — A survey is presented of results from some recent searches for new physics in final states with jets or vector bosons such as dijet, black holes, massive resonances or vector-like quarks searches. The results are based on 13 TeV or 8 TeV proton-proton collisions data collected by the CMS detector at the LHC.

1. – Introduction

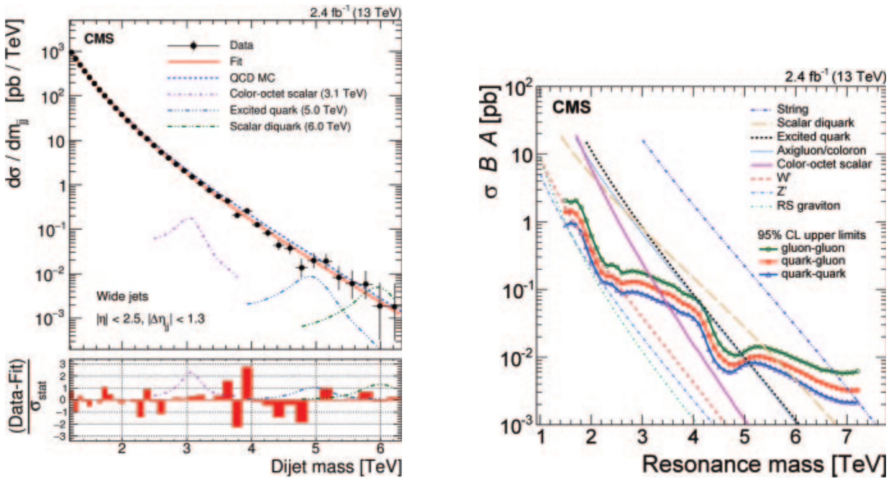
The Standard Model of particles physics is a very successfull but incomplete theory. Many theories beyond the SM (BSM) try to address some of the SM weaknesses and signatures of eventual new physics would manifest themselves in collisions at the LHC. We present here an overview of CMS searches for new physics in final states with jets or bosons. A detailed description of the CMS detector can be found in [1].

2. – Dijet search

2˙1. *Search for narrow resonances in dijet mass distribution.* – A search for narrow resonances in pp collisions at $\sqrt{s} = 13$ TeV has been performed [2]. Collected data correspond to an integrated luminosity of $2.4\,\text{fb}^{-1}$.

Jets with $p_T > 40\,\text{GeV}$ and $|\eta| < 3$ are used to compute the H_T variable which is the scalar sum of the jets p_T. We select events with $H_T > 800\,\text{GeV}$ or containing a jet with $p_T > 500\,\text{GeV}$. To reduce the analysis sensitivity to gluon radiation from the final state parton, geometrically close jets are combined into "wide jets": the two leading jets of the event are used as seeds the 4-vectors of all the other jets, if they fall within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.1$, are added to the nearest leading jet to obtain two wide jets which then form the dijet system. We require the wide jet to satisfy $|\Delta\eta_{jj}| < 1.3$ to suppress the background from t-channel dijet events. Finally, events are required to satisfy $m_{jj} > 1.2\,\text{TeV}$ for which the combined L1 trigger and HLT are found to be fully sufficient.

We compare the dijet mass spectrum obtained for data with a leading-order QCD Monte Carlo (MC) prediction (fig. 1(a)): there is no evidence for a narrow resonance in



(a) (b)

Fig. 1. – (a) Inclusive dijet mass spectrum. (b) Observed 95% C.L. upper limits on $\sigma \times B \times A$. Limits are compared to the predicted cross section of different models.

the data. Thus we set upper limits at 95% confidence level (C.L.) on signal cross section (σ) $\times$ the branching ratio (B) $\times$ the acceptance (A) as a function of the dijet resonance mass. These cross section limits are compared to the one predicted by specific new physics models which may produce quark-gluon, quark-quark or gluon-gluon resonances (fig. 1(b)).

The mass limits represent significant extensions of the most stringent observed limits from LHC Run 1. For string resonances, the observed mass limit is 7.0 TeV; for scalar diquarks, the observed mass limit is 6.0 TeV; for axigluons and colorons, the observed mass limit is 5.1 TeV; for excited quarks, we set a mass limit of 5.0 TeV; for a color-octet scalar, the observed mass limit is 3.1 TeV; and for a W′ boson, we exclude masses up to 2.6 TeV.

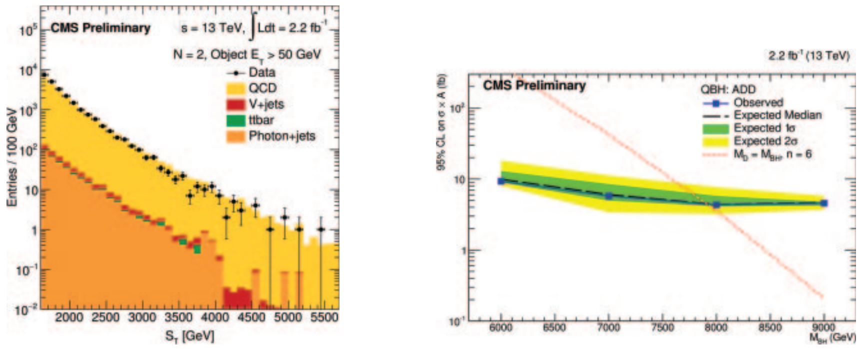
2˙2. *Search for NP signatures in dijet angular distribution.* – We present here a search for quark contact interactions (CI) and extra spatial dimensions as proposed in the ADD model using dijet angular distributions in pp collisions at $\sqrt{s} = 13\,\text{TeV}$ (integrated luminosity: $2.6\,\text{fb}^{-1}$) [3].

Events are selected using a HLT trigger based on H_T ($H_T > 650$–$800\,\text{GeV}$ depending on the run). The two highest p_T jets are used to measure in several m_{jj} regions the angular distributions which is expressed in terms of $\chi_{\text{dijet}} = \exp(|y_1 - y_2|)$ where y_1 and y_2 are the rapidities of the two leading jets. We require $\chi_{\text{dijet}} < 1.6$ and $|1/2(y_1 + y_2)| < 1.11$.

The distributions are found to be in good agreement with predictions from perturbative QCD. Quark CI are excluded at 95% C.L. to a scale of 12.1 (16.3) TeV for destructive (constructive) interference, and the lower limits for the scales of ADD models are in the range 7.7–10.8 TeV.

3. – Inclusive black holes search for all possible final states

This search [4] is performed using pp collisions at $\sqrt{s} = 13\,\text{TeV}$ (integrated luminosity: $2.2\,\text{fb}^{-1}$) and is inclusive as it is looking for black holes decaying in all possible energetic



(a) (b)

Fig. 2. – (a) S_T spectrum for multiplicity $N = 2$. (b) Observed and expected upper 95% C.L. cross section times acceptance limits overlaid with the predicted values for quantum black holes.

multiparticle final states, dominated by multijet ones in the semiclassical black hole case and dijet one for the quantum black hole case.

The discriminating variable is S_T defined as the scalar sum of transverse energies of all energetic objects (jets, electrons, muons, photons) in the event provided they satisfy $E_T > 50\,\text{GeV}$ plus the missing transverse energy E_T^{miss} (if $E_T^{\text{miss}} > 50\,\text{GeV}$). We then consider S_T distributions in various inclusive oject multiplicity bins (as represented in fig. 2(a)), where the signal, if it exists, would manifest in a broad enhancement at the high end.

As no excess is found, we proceed to set a 95% C.L. lower limit on $M_{\text{BH}}^{\text{min}}$ defined as the threshold mass for black hole production: semiclassical black holes with masses below 8.7 TeV and quantum black holes (whose limits are represented in fig. 2(b)) with masses below 8 TeV are excluded. These results are more stringent than the previously obtained limits in Run 1.

4. – Massive resonances search

4·1. *Searches for massive resonances decaying to VV (V=W,Z).* – The two analyses presented here are based on pp collision data at $\sqrt{s} = 13\,\text{TeV}$ ($2.6\,\text{fb}^{-1}$) [5]. Two channels are considered: either both bosons decay hadronically, or one W decays leptonically while the other vector boson decays hadronically. In both cases, as the hadronically decaying boson is boosted, its decay products are merged into a single jet identified using a dedicated "V-tagging" technique: we require its pruned mass(1) to be close to the mass of the boson from which it originates ($65 < M_{V\text{jet}} < 85\,\text{GeV}$ for the W-candidate and $85 < M_{V\text{jet}} < 105\,\text{GeV}$ for the Z-candidate) and we look for two subjets, using the N-subjettiness variable τ_N(2) ($\tau_{21} = \tau_2/\tau_1 > 0.75$). For the semileptonic channel, we require exactly one isolated muon (electron) with $p_T > 53(120)\,\text{GeV}$ and $|\eta| < 2.1(2.5)$,

(1) The pruning algorithm is a jet grooming algorithm, that improves the resolution on the jet mass and reduces the effect of pileup by re-clustering the jet constituents while applying additional requirements that eliminate soft, large-angle quantum chromodynamic (QCD) radiations [6].
(2) The N-subjettiness variable τ_N quantifies the tendency of a jet to be composed of N subjets, having smaller values for jets with a N-subjets–like configuration [7].

and $E_T^{\text{miss}} > 40(80)\,\text{GeV}$. Events are categorised depending on the V-jet "flavour" (W or Z), τ_{21} and, in addition for the semileptonic channel, the lepton flavour.

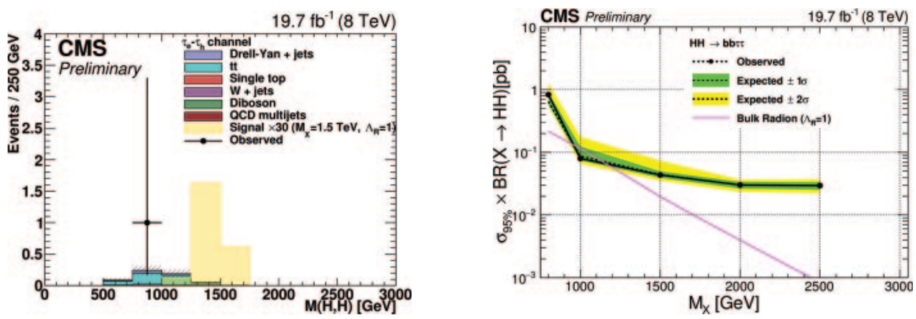
No evidence of signal is seen in the diboson mass distributions. 95% C.L. upper limits are set for the production cross section of the HVT (model B) $\text{W}' \to \text{WZ}$ in the range [755-5.7] fb; of the bulk graviton $\to$ WW in the range [472-4.0] fb; and of the bulk graviton $\to$ ZZ in the range [227-6.8] fb. Moreover, a lower limit of 2 TeV is set on the HVT (model B) W′ mass.

4·2. *Resonant pair production of Higgs bosons decaying to $b\bar{b}\tau^+\tau^-$.* – We perform a search for a massive resonance decaying into two Higgs bosons, one decaying to $b\bar{b}$ and the other to $\tau^+\tau^-$ [8]. We use 2012 data collected at $\sqrt{s} = 8\,\text{TeV}$, corresponding to an integrated luminosity of $19.7\,\text{fb}^{-1}$.

The two b jets coming from one of the boosted H are merged to a single wide jet which is identified through a study of its pruned mass ($100 < m_{\text{jet}} < 140\,\text{GeV}$ so close to the Higgs boson mass), its substructure ($\tau_{21} < 0.75$) consistent with the presence of b quarks (applying b-tagging to the subjets). Similarly, the two τ leptons are overlapping and advanced techniques are used for their reconstruction and identification in events where one τ decays hadronically and the other decays into an electron or a muon. We require at least one jet with $p_T > 400\,\text{GeV}$ and $|\eta| < 1.0$. Leptons are required to have $p_T > 10\,\text{GeV}$ and $|\eta| < 2.5(2.4)$ for electrons (muons). Finally, an event is selected if $E_T^{\text{miss}} > 50\,\text{GeV}$ to reduce multijet background.

Looking at di-Higgs invariant mass distributions, as represented in fig. 3(a), no significant deviation is found between the observed and the expected numbers of events: the analysis sets 95% C.L. upper limits on the production cross section of a spin-0 resonance ranging from 850 to 30 fb for masses between 800 and 2500 GeV in the HH final state. Masses of Kaluza-Klein (KK) excitation of spin-0 particle (radion) with ultraviolet mass scale $\Lambda_R = 1\,\text{TeV}$ are excluded between 950 and 1150 GeV, as represented in fig. 3(b).

4·3. *Search for W′ decaying to tb ($t\bar{b} + \bar{t}b$).* – We search for a heavy charged gauge boson W′ decaying into a top quark and a bottom quark at $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of $2.2\,\text{fb}^{-1}$ [9]. We analyze the lepton (e, μ) plus jets and E_T^{miss} signature resulting from the decay chain $\text{W}' \to \text{tb}$, $\text{t} \to \text{bW} \to \text{b}l\nu$, and we focus on W′ with purely right-handed couplings and narrow widths.



(a) (b)

Fig. 3. – (a) Number of background and signal events with full selection applied in the electron channel. (b) Expected and observed upper limits on the cross section of radion decaying into Higgs bosons.

Exactly one muon (electron) is required to be within the detector acceptance, *i.e.* $|\eta| < 2.1(2.5)$, and to have $p_T > 180\,\text{GeV}$. As the W′ boost is causing the b-jet and lepton decay products to be close to each other, we do not require lepton to be isolated. To reduce multijet background, the selected lepton is required to satisfy $\Delta R(\text{lepton, nearest jet}) > 0.4$ or $p_T^{\text{rel}}(\text{muon, nearest jet}) > 50\,\text{GeV}$ or $p_T^{\text{rel}}(\text{electron, nearest jet}) > 60\,\text{GeV}$ where p_T^{rel} is the magnitude of the lepton momentum orthogonal to the jet axis. We veto additional muons (electrons) with $p_T > 35\,\text{GeV}$ and $|\eta| < 2.4(2.5)$. There must be at least two jets in the event with $p_T^{j_1} > 450(350)\,\text{GeV}$ and $p_T^{j_2} > 30\,\text{GeV}$, and $E_T^{\text{miss}} > 50(120)\,\text{GeV}$ in the muon (electron) channel.

As we find no evidence of W′ production in the tb invariant mass distributions, we calculate 95% C.L. upper limits on the production cross sections × branching fraction for W′ → tb and exclude W′ masses below 2.38 TeV. These results already exceed their 8 TeV counterparts where masses below 2.15 TeV were excluded after the combination of the hadronic and leptonic channel [10].

4·4. *Search for $t\bar{t}$ resonances in boosted semileptonic final state.* – Numerous BSM models predict gauge interactions with enhanced couplings to third-generation quarks, especially the extremely heavy top quark. In this analysis, we perform a model-independent search for massive resonances decaying to $\text{t}\bar{\text{t}}$ at $\sqrt{s} = 13\,\text{TeV}$ (integrated luminosity of $2.6\,\text{fb}^{-1}$) [11].

The selection is optimized for highly boosted top quarks. We select events containing one non-isolated muon (electron) with $p_T > 50\,\text{GeV}$ and $|\eta| < 2.1(2.5)$ and at least two jets with $|\eta| < 2.4$ and $p_T > 150(250)/50(70)\,\text{GeV}$. Even if no isolation requirements are placed on the leptons, events have to pass a two-dimensional criterion given by $\Delta R(l, j) > 0.4$ or $p_T^{\text{rel}}(l, j) > 20\,\text{GeV}$ (where j is the closest jet). In addition, in the muon channel, we require $H_T^{\text{lep}} = E_T^{\text{miss}} + p_T^{\text{lep}} > 150\,\text{GeV}$ with $E_T^{\text{miss}} > 50\,\text{GeV}$. In the electron channel, we require $E_T^{\text{miss}} > 120\,\text{GeV}$. The kinematical reconstruction of the $\text{t}\bar{\text{t}}$ system is performed by using a two-term χ^2 discriminator. Informations from t-tagging and b-tagging algorithms are also used to further enhance the sensitivity. Events are categorized according to the lepton flavour and the numbers of b-tagged and t-tagged jets.

Looking at the $\text{t}\bar{\text{t}}$ invariant mass spectrum, no significant deviation from the expected SM background is observed in the data: we set 95% C.L. upper limits on the cross section times branching ratio. Results are interpreted in the context of leptophobic topcolor Z bosons (with different width hypothesis) and KK excitations of a gluon in the Randall-Sundrum model, as summarized in table I. This analysis has approximately the same sensitivity as the previous search based on 8 TeV data [12].

TABLE I. – *Expected (observed) 95% C.L. signal mass exclusion limit (TeV) for different $t\bar{t}$ resonances hypothesis, for both 13 TeV (semileptonic channel) and 8 TeV (combination of hadronic, semileptonic and dileptonic channels) data.*

Signal	13 TeV ($l + jets$)	8 TeV (comb.)
Z′, $\Gamma_{Z'}/M_{Z'} = 1\%$	2.1 (2.3)	2.4 (2.4)
Z′, $\Gamma_{Z'}/M_{Z'} = 10\%$	3.5 (3.4)	2.8 (2.9)
Z′, $\Gamma_{Z'}/M_{Z'} = 30\%$ ($M_{Z'} > 1\,\text{TeV}$)	4.0 (4.0)	–
RS KK gluon	2.9 (2.9)	2.7 (2.8)

5. – Search for vector-like quarks (VLQs)

Vector-like quarks are fermions which are predicted in BSM models including little Higgs, composite Higgs and those including extra-dimensions. New VLQs would be able to solve the hierarchy problem by canceling the divergent radiative corrections to the Higgs mass. Another feature of these new particles is that their left- and right-handed components transform in the same way under the SM symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$ (they have vector couplings while SM quarks have V-A couplings). This allows direct mass terms in the Lagrangian of the form $m\bar{\Psi}\Psi$ that do not violate gauge invariance. As a consequence, vector-like quarks do not acquire their mass via Yukawa couplings, in contrast to the other quarks families.

5˙1. *Search for vector-like $T\bar{T}$ and $B\bar{B}$: legacy results from Run 1.* – We summarize here the results obtained from Run 1 data of the searches for vector-like T and B quarks with charge 2/3 and −1/3 respectively, which are both strongly produced in pairs. T can decay into tH, tZ, bW, and B can decay into tW, bZ or bH. All the details about these searches can be found in [13, 14]. For T, depending on the branching ratio, expected (observed) 95% C.L. limits are in the range [790, 890] GeV ([720, 920] GeV). For the B, depending on the branching ratio, expected (observed) 95% C.L. limits are in the range [710, 890] GeV ([740, 900] GeV).

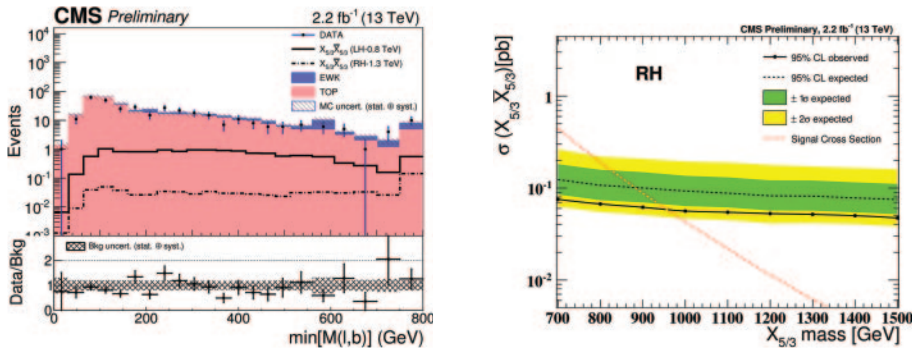
5˙2. *Search for $Q\bar{Q}$.* – A seach for strong production of of heavy quark pairs $\mathrm{Q\bar{Q}}$ and their subsequent decay $\mathrm{Q\bar{Q} \to qW^+\bar{q}W^- \to ql\nu\bar{q}q\bar{q}'}$, where q denotes a down-type light quark, has been performed using 8 TeV data [15]. The search is jointly performed for $\mathrm{T\bar{T} \to bW^+\bar{b}W^- \to bl\nu\bar{b}q\bar{q}'}$ whose results have been used for the combination limits presented in the previous section, but we focus here on $\mathrm{Q\bar{Q}}$.

Selected events must contain exactly one charged muon (electron) with $p_T > 45(30)$ GeV and $|\eta < 2.1(2.5)|$ and E_T^{miss} 20(30) GeV. We veto events with a second muon (electron) with $p_T > 10(20)$ GeV and $|\eta| < 2.5$. As both resolved and boosted topologies for the hadronically decaying W are taken into account, we require at least four jets: either at least four narrow jets, or at least three narrow jets and at least one wide jet. If a wide jet mass fulfills the cut $60 < m_j < 100$ GeV, we assign it a "W-tag". We then apply a more or less stringent b-tag veto depending of the presence of a W-tag jet or not. We obtain the Q mass from a constraint kinematic fit. In addition, the cut $S_T = p_T^l + E_T^{\text{miss}} + p_T^{J1} + p_T^{J2} + p_T^{J3} + p_T^{J4} > 1240$ GeV highly suppresses the $\mathrm{t\bar{t}}$ dominant background.

As no significant deviation from SM expectations is observed in data Q mass distributions, we proceed to set limits on production cross section and exclude vector-like Q quark with mass below 788 GeV at 95% C.L.

5˙3. *Search for $X_{5/3}\bar{X}_{5/3}$.* – A search for the production of heavy partners of the top quark with charge 5/3 (denoted as $\mathrm{X_{5/3}}$) has been performed using 13 TeV data (2.2 $\mathrm{fb^{-1}}$) [16]. We assume that $\mathrm{X_{5/3}}$ decays via $\mathrm{X_{5/3} \to tW^+ \to bW^+W^+}$, and we focus on two different final states: in the dilepton channel, the two W arising from one of the $\mathrm{X_{5/3}}$ decay into same-sign leptons while the other two W decay inclusively; in the semileptonic channel, one W decays leptonically into a lepton and a neutrino, while the other three W decay hadronically.

For the same-sign dilepton channel, dedicated algorithms are used to identify the charge of the electrons and optimized to reduce charge misidentification. We require two same-sign leptons with $p_T > 30$ GeV. In addition, we apply a quarkonia veto



(a) (b)

Fig. 4. – (a) Distribution of min$[M(l,b)]$ in the $\geq$ boosted W-tagged jets and 1 b-tagged jet category for combined electron and muon samples. (b) 95% C.L. expected and observed upper limits after combining the same-sign dileptons, and the lepton+jets signatures for right-handed $X_{5/3}$ signals.

($M_{ll} > 20$ GeV) and a Z-boson veto (rejects events with M_{ll} within 15 GeV of M_Z and, for dielectron channel only, $M_{ll} > 106.1$ GeV or $M_{ll} < 76.1$ GeV). Selected jets are required to have $p_T > 30$ GeV and $|\eta| < 2.5$. We require the leading lepton to have $p_T > 40$ GeV, the number of constituents (jets and other leptons not in the same-sign pair) of at least five and $H_T^{\rm lep} > 900$ GeV (where $H_T^{\rm lep}$ is the scalar sum of the p_T of all selected jets and leptons). For this channel, the relevant variable to look at for the hunt of a new signal is $H_T^{\rm lep}$. $E_T^{\rm miss}$ is used for background estimation using data-driven techniques.

For the semileptonic channel, we require one lepton to have $p_T > 80$ GeV, $E_T^{\rm miss} > 100$ GeV and at least four jets and one b-tagged jet. We also use W-tagging techniques to identify boosted hadronic W decays: the arised wide jet is tagged as W if its mass is between 65 and 105 GeV and if $\tau_2/\tau_1 < 0.55$. We require at least one W-tagged jet to have $p_T > 200$ GeV. Finally, we apply a cut on the distance between the lepton and the subleading jet: $\Delta R(l, \text{subleading jet}) > 1.0$. The main discriminating variable for this channel is the mass reconstructed from the lepton and the b-tagged jet, labeled M(l,b). In case more than one jet is b-tagged, the minimum mass from the possible lepton b-tagged jet pairs min$[M(\mathrm{l},\mathrm{b})]$, represented in fig. 4(a), is used.

No significant excess in the data over the background prediction is observed neither in $H_T^{\rm lep}$ distribution for the dilepton channel, nor in the min$[M(\mathrm{l},\mathrm{b})]$ spectrum for the semileptonic channel; we compute 95% C.L. upper limits on signal production cross section for both channels. A combination of the results from the two analyses sets the observed (expected) exclusion limit on the mass of a right-handed $\mathrm{X}_{5/3}$ of 960 (900) GeV, represented in fig. 4(b). For the left-handed $\mathrm{X}_{5/3}$, the observed (expected) lower limit on the mass is 940 (860) GeV.

6. – Conclusion

In conclusion, we have presented several recent BSM searches by CMS covering many final states and many benchmark models of BSM scenarios. Even if no sign of new physics beyond the SM has been found —yet—, the Run1 analyses have allowed to establish limits on several BSM processes. First 13 TeV results already allow to push the limits further, despite the integrated luminosity being an order of magnitude smaller, which is really promising. Future Run2 data analyses will continue with enthusiams and will give new answers, as they will pursue to scrutinize higher-energy processes and reach better sensitivity.

REFERENCES

[1] CMS Collaboration, *JINST*, **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
[2] CMS Collaboration, *Phys. Rev. Lett.*, **116** (2016) 071801, arXiv:1512.01224 [hep-ex].
[3] CMS Collaboration, CMS-PAS-EXO-15-009 (2015).
[4] CMS Collaboration, CMS-PAS-EXO-15-007 (2015).
[5] CMS Collaboration, CMS-PAS-EXO-15-002 (2016).
[6] Ellis S. D., Vermilion C. K. and Walsh J. R., *Phys. Rev. D*, **80** (2009) 051501, arXiv:0903.5081.
[7] Thaler J. and Van Tilburg K., *JHEP*, **03** (2011) 015, arXiv:1011.2268 [hep-ph].
[8] CMS Collaboration, CMS-PAS-EXO-15-008 (2015).
[9] CMS Collaboration, CMS-PAS-EXO-15-004 (2015).
[10] CMS Collaboration, *JHEP*, **02** (2016) 122, arXiv:1509.06051 [hep-ex].
[11] CMS Collaboration, CMS-PAS-B2G-15-002 (2016).
[12] CMS Collaboration, *Phys. Rev. D*, **93** (2016) 012001, arXiv:1506.03062 [hep-ex].
[13] CMS Collaboration, *Phys. Rev. D*, **93** (2016) 012003, arXiv:1509.04177 [hep-ex].
[14] CMS Collaboration, CMS-B2G-13-006 (2015), submitted to *Phys. Rev. D*.
[15] CMS Collaboration, CMS-PAS-B2G-12-017 (2014).
[16] CMS Collaboration, CMS-PAS-B2G-15-006 (2015).