SEARCHING FOR EXOTIC PHYSICS BEYOND THE STANDARD MODEL: EXTRAPOLATION UNTIL THE END OF RUN-3

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The prospects of looking for exotic beyond-the-Standard-Model physics with the ATLAS and CMS detectors at the LHC in the rest of Run-2 and in Run-3 will be reviewed. A few selected analyses will be discussed, showing the gain in sensitivity that can be achieved by accumulating more data and comparing the current limits with the predicted reach. Some limiting factors will be identified, along with ideas on how to improve on the searches.

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1 Introduction

Since the beginning of Run-2 in 2015 and up to the end of 2016, the LHC delivered around 45 fb^{-1} of proton-proton collision data at a centre-of-mass energy of 13 TeV. Data taking at the same energy should resume in June 2017, accumulating another 45 fb^{-1} by the end of the year, thanks to an instantaneous luminosity which is expected to reach up to 1.9×10^{34} cm^2s^{-1}. Run-2 will finish at the end of 2018, with an expected total of 120 fb^{-1} delivered to the ATLAS and CMS experiments.

Run-3 is scheduled to start in 2021, after a two-year shutdown which will be devoted to maintenance and upgrades of both the LHC and the detectors, possibly allowing to run at the nominal centre-of-mass energy of 14 TeV. It will last until the end of 2023, with the goal of delivering around 300 fb^{-1}.

The significant increase expected in the dataset size will offer the opportunity to search more thoroughly for physics beyond the Standard Model (SM) in various sectors, as will be described in the next sections.

2 Searching for Dark Matter Candidates

2.1 Events Containing a Jet and Large Missing Transvserse Momentum

If dark-matter (DM) candidates are pair produced at the LHC, they are invisible to the detector: one needs to rely on an object, such as an initial-state-radiation (ISR) jet with high transverse momentum (p_{T}), in order to tag the events and measure the recoiling DM candidates as large missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$). The SM backgrounds are further suppressed by requiring the $E_{\mathrm{T}}^{\mathrm{miss}}$to be well separated from the jets and by vetoing events which contain other objects, such as electrons, muons, or too many extra jets. The main background, $Z(\rightarrow \nu\bar{\nu})$+jets, is estimated by normalising the Monte Carlo yields in control regions (CRs) enriched in $W(\mu\nu)$+jet events (an additional γ+jet CR, which benefits from higher statistics than the leptonic CR, can also be used).

Projection studies for the reach of this analysis as a function of the integrated luminosity L_{int} (5 to 3000 fb^{-1}) were performed before the start of Run-2 [1]. They are therefore based on the DM production model which was used at the time, namely an effective field theory (EFT) with a vector-like operator, characterised by a suppression scale M_*. These studies showed that the limit which can be set on M_* quickly reaches a plateau after L_{int}=5 fb^{-1} if the same analysis selections are kept ($E_{\mathrm{T}}^{\mathrm{miss}} > 400$ GeV), as the analysis starts being dominated by systematic uncertainties. The limits can however be pushed towards significantly higher M_* values by requiring higher $E_{\mathrm{T}}^{\mathrm{miss}}$ thresholds as L_{int} increases, or by reducing the systematic uncertainties below the assumed 5% level: going down to 1% would translate into a 0.5 TeV gain in M_*. The DM model considered changed in Run-2, following the ATLAS/CMS DM Forum recommendations [2]: simplified models with an explicit s-channel mediator are used in order to avoid the EFT validity issues. These tend to have a softer $E_{\mathrm{T}}^{\mathrm{miss}}$ spectrum with respect to EFT models, which could somewhat change the conclusions of the perspective studies: while adding new signal regions (SRs) at higher $E_{\mathrm{T}}^{\mathrm{miss}}$ values would still be interesting, these will not necessarily dominate the sensitivity as is the case for the EFT models.

The ATLAS Run-2 analysis[3] performed on the 3.2 fb^{-1} 2015 dataset uses multiple SRs, with various $E_{\mathrm{T}}^{\mathrm{miss}}$ thresholds, the highest one being $E_{\mathrm{T}}^{\mathrm{miss}}> 700$ GeV. The limits reach the TeV scale in the mediator mass, and the highest-$E_{\mathrm{T}}^{\mathrm{miss}}$ SR is dominated by statistical uncertainties (10%, while the total uncertainty is 12%). There are however important systematic uncertainties, at the level of 4%, in the highest-$E_{\mathrm{T}}^{\mathrm{miss}}$ SR, associated with the use of the W CR for the Z background estimation. They come from differences in the electroweak radiative next-to-leading-order corrections of the W+jets and Z+jets processes. These could quickly become a limiting factor, especially at high values of $E_{\mathrm{T}}^{\mathrm{miss}}$, as they increase with the boson p_{T}. This issue is currently being addressed in the LHC Dark Matter Working Group.[a]

2.2 The Higgs-to-Invisible Decay Channel

The Higgs boson could potentially decay into a pair of DM candidates if these are sufficiently light, leading to an *invisible Higgs* signature. Predictions on the sensitivity of such a search were done before the start of Run-2 [4,5], considering the $Z(\ell\ell)H(inv)$ associated-production channel. They are reported in table 1. Two scenarios are considered: the best scenario, which assumes that the systematic uncertainties will scale down as ${L_{int}}^{-1/2}$ (the CMS Collaboration considers the theoretical uncertainties to be halved in this scenario), and the conservative scenario, in which the systematic uncertainties remain unchanged with respect to Run-1.

Table 1: Limits at the 95% confidence level on the Higgs-to-invisible branching ratio, as expected in the $Z(\ell\ell)H(inv)$ channel for 300 fb^{-1} of 14 TeV data, compared with the Run-1 limits [6,7] in this channel.

	CMS	ATLAS
Best scenario	17%	23%
Conservative scenario	28%	32%
Run-1 observed (expected) limit	81% (83%)	75% (62%)

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[a] http://lpcc.web.cern.ch/LPCC/index.php?page=dm_wg

While significantly lower limits on the invisible branching ratio can be obtained with more data in this channel, even in the conservative scenario, the most sensitive channel currently is the vector-boson-fusion (VBF) channel, for which the expected limit obtained by the CMS Collaboration is already at the 30% level when combining the Run-1 dataset with 2.3 fb^{-1} of Run-2 data [8]. As in the jet+$E_{\mathrm{T}}^{\mathrm{miss}}$ analysis discussed in section 2.1, the main background in the VBF channel is $Z(\rightarrow \nu\bar{\nu})$+jets and it is estimated using a $W(\rightarrow \mu\nu)$ CR: it is thus also important for this analysis to see the Z/W ratio theoretical uncertainty reduced.

3 Searching for Di-jet Resonances

Another staple of exotica searches at the LHC is to look for resonant structures which could appear on top of the smoothly-falling SM dijet mass (m_{jj}) spectrum: the shape of the SM background m_{jj} distribution is fitted with a functional form of the type $f_4(x) = p_1(1-x)^{p_2}x^{p_3+p_4 \ln x}$, where the p_i with $i = 1, 2, 3, 4$ are the free parameters, and $x \equiv m_{\mathrm{jj}}/\sqrt{s}$.

3.1 Exploring Higher Masses

The expected limit was studied as a function of L_{int} for some benchmark scenarios [9], including an excited quark (q^*) production model. With 25 fb^{-1} of 14 TeV data, the expected limits was predicted to be $m_{q^*} > 6.6$ TeV, while the current expected limit with 37.0 fb^{-1} of 13 TeV data [10] is slightly worse, at 5.8 TeV. While this channel mainly benefits from an increase in the centre-of-mass energy (the Run-1 limits obtained with 20.3 fb^{-1} of 8 TeV data[11] were superseded with less than 0.1 fb^{-1} of 13 TeV data[12]), there is still some gain which can come from simply accumulating data until the end of Run-3, with a $m_{q^*} > 7.4$ TeV limit predicted for 300 fb^{-1}.

3.2 Exploring Lower Masses

While the search continues to explore the high-m_{jj} tail, there are also some recent analysis developments at the other end of the spectrum. It is indeed interesting to probe for more weakly coupled resonances in the bulk of the distribution, at low dijet masses. There, the analysis faces the issue of the jet-trigger threshold. The lowest unprescaled single-jet trigger used in Run-2 so far by ATLAS requires $p_T^{\mathrm{jet}} > 440$ GeV: this translates into a TeV-scale m_{jj} threshold for the search. There are two ways to go below this mass threshold: using data scouting or requiring the presence of a high-p_{T} ISR object.

Data scouting relies on the fact that the limiting factor is the trigger bandwidth, which is directly proportional to the event rate and the size of the events. While the rate of low-mass dijet events is very large at the LHC, one can play with the event size by performing part of the analysis at the trigger level, saving only the relevant part of the data. When used on 27 fb^{-1} of 13 TeV data, this technique allowed the CMS Collaboration to probe m_{jj} values down to 600 GeV [13].

The other idea is to trigger on a high-p_{T} ISR jet or photon. While this ISR requirement lowers the signal-selection efficiency, it also allows to probe very low values of m_{jj}: the search for a resolved resonance in ATLAS was in this way able to cover the 169–1493 GeV range in 15.5 fb^{-1} of 13 TeV data [15]. Very-low-mass resonances can also be boosted against the high-p_{T} ISR: a targeted analysis by the CMS Collaboration, using jet substructure techniques, was able to set limits in the 100–300 GeV range using 2.7 fb^{-1} of 13 TeV data [14].

3.3 Exploring New Interpretations

Another recent development in the dijet searches is their interpretation in the context of DM models. Indeed, if DM candidates can be produced at the LHC through an s-channel mediator, as described in section 2.1, then this mediator could also decay back to jets. The dijet resonance search can hence be used to set limits in the DM mass/mediator mass plane for given couplings of the mediator to quarks and to DM candidates . The interplay of the dijet resonance and the jet+$E_{\mathrm{T}}^{\mathrm{miss}}$ searches depends heavily on these couplings, and the development of both types of analyses with more data will allow to explore a larger parameter space.

4 Searching for New Gauge Bosons

Multiple theories beyond the SM postulate the existence of extra gauge bosons, which can be probed in various channels.

4.1 The Dilepton Resonance Search

For example, a dilepton resonance search can be used to look for a so-called *sequential SM Z'*, which has the same fermionic couplings as the SM Z boson. In this search, the main Z-boson background is estimated using a Monte Carlo simulation which is normalised in the low dilepton mass region. Such a Z' could be discovered by the end of Run-3 in this channel if its mass is below 5.1 TeV [4]. For comparison, the mass limit currently placed on this model by the CMS Collaboration is around 3.6 TeV when analysing 13.0 fb^{-1} of 13 TeV data [16], including an extra 1.3 scale factor on the production cross-section to take into account higher-order effects. There is thus still some room to cover in this search, and as for the dijet resonance searches, this search has recently started investigating its potential interplay with DM searches.

4.2 Searching for a $W' \to \ell\nu$

The leptonic decay of a heavy W' can instead be probed by looking for an excess in the tail of the lepton–$E_{\mathrm{T}}^{\mathrm{miss}}$ transverse mass distribution. Again, one can push the limits to higher mass values than the currently excluded 5.11 TeV [18] with the data which will be accumulated by the end of Run-3 [4], but another interesting avenue to explore with the extra data, as in the dijet low-mass case, is the possibility of smaller couplings in the bulk of the distribution. Prospective studies [17] show that the discovery reach could gain a factor of around 2 in the coupling strength, depending on the W' mass, by the end of Run-3.

4.3 Di-top Resonances

In some models such as topcolour assisted technicolour, the Z' can preferentially decay into top-quark pairs, giving rise to a $t\bar{t}$ resonance. In this search, which uses large jets with substructure techniques at high masses, the main $t\bar{t}$ SM background is estimated using a Monte Carlo simulation. Prospective studies indicate that a topcolour Z' mass of 3 TeV could be excluded by the end of Run-3 if no excess is seen [9], while the current mass limit placed by the ATLAS Collaboration in this channel is around 2 TeV with 3.2 fb^{-1} of 13 TeV data [20]. In this study, the main systematic uncertainties (related to the background normalisation and the large jets) are conservatively taken to be at the same level as they currently are; these could however most probably be reduced with a larger dataset which should allow for a better comprehension of the $t\bar{t}$ background and of the large jets.

5 Vector-Like Top Quarks

Third-generation quarks are also used in the search for heavy vector-like T quarks, which are predicted by some Higgs compositeness models and which would decay to bW, Ht and Zt final states. Prospective studies of the discovery reach as a function of L_{int} were performed by the CMS Collaboration [4], based on the Run-1 searches for the pair production of such particles through strong interaction. Eight signal regions are considered in the search, requiring at least one electron or muon, a number of jets identified as originating from b-quarks, and a boosted W or Z boson. The predicted discovery reach is about 1.3 TeV for the T mass by the end of Run-3, while the current limit obtained by the CMS Collaboration is around 750 GeV with 2.3 fb^{-1} of 13 TeV data[21]. The single-T production is also a promising channel which is being thoroughly explored, with many analyses already performed in Run-2[22]: while these analyses are more model dependent than the search for pair production (as the production depends on the couplings), they can reach higher T masses.

6 Long-lived Particles

A sector which will be of increased importance in the years to come is the search for long-lived particles. Models predict a plethora of final states which have not yet all been thoroughly investigated, as they can lead to particularly challenging experimental signatures: displaced vertices, out-of-time decays, emerging jets, disappearing tracks, heavy stable charged particles, etc. These final states not only often necessitate rewriting parts of the reconstruction algorithms, they can also require dedicated triggers which may not have been in place in earlier data taking. They can also suffer from rare experimental backgrounds which need involved studies, leading to longer data-to-publication times. There is currently an ongoing effort between the LHC experiments and theorists to produce a white paper on this topic by the end of the year 2017.[b] The aim is to ensure the best possible coverage for such signatures by identifying the gaps in the current coverage, new search ideas, and possible ways to present the results to ease later re-interpretation.

7 Conclusions

The 13 TeV dataset should increase by roughly a factor of three by the end of Run-2 in 2018. After the second long shutdown, data taking should resume in 2021, possibly at a centre-of-mass energy of 14 TeV, with Run-3 lasting until the end of 2023. By then, 300 fb^{-1} are expected.

Searches for physics beyond the SM will continue to explore uncharted territories as more data will populate the tail of kinematic distributions and as smaller new-physics couplings will be probed in the bulk of these distributions.

The improvements in these searches will come from many sources. First, by continuing to improve on the selection of existing analyses as data is taken, and by reducing some relevant systematic uncertainties as data allows to understand better some objects and SM backgrounds. Second, by finding ways of maintaining the excellent performance in an increasingly challenging high-pileup environment, as both experiments have done so far. Third, by including theoretical improvements on the SM predictions. And finally, by continuing to develop new analyses to leave no stone unturned.

References

1. ATLAS Collaboration, ATL-PHYS-PUB-2013-007, http://cds.cern.ch/record/1564937.
2. D. Abercrombie et al., arXiv:1507.00966.
3. ATLAS Collaboration, *Phys. Rev.* D **94**, 032005 (2016).
4. CMS Collaboration, CMS-NOTE-13-002, arXiv:1307.7135.
5. ATLAS Collaboration, ATL-PHYS-PUB-2013-014, http://cds.cern.ch/record/1611186.
6. CMS Collaboration, *Eur. Phys. J.* C **74**, 2980 (2014).
7. ATLAS Collaboration, *Phys. Rev. Lett.* **112**, 201802 (2014).
8. CMS Collaboration, *JHEP* **02**, 135 (2017).
9. ATLAS Collaboration, ATL-PHYS-PUB-2015-004, http://cds.cern.ch/record/2002136.
10. ATLAS Collaboration, arxiv:1703.09127, submitted to *Phys. Rev.* D.
11. ATLAS Collaboration, *Phys. Rev.* D **91**, 052007 (2015).

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[b] See for example this workshop: `https://indico.cern.ch/event/607314/`.

12. ATLAS Collaboration, ATLAS-CONF-2015-042, http://cds.cern.ch/record/2048113.
13. CMS Collaboration, CMS-PAS-EXO-16-056, http://cds.cern.ch/record/2256873.
14. CMS Collaboration, CMS-PAS-EXO-16-030, http://cds.cern.ch/record/2202715.
15. ATLAS Collaboration, ATLAS-CONF-2016-070, http://cds.cern.ch/record/2206221.
16. CMS Collaboration, CMS-PAS-EXO-16-031, http://cds.cern.ch/record/2205764.
17. CMS Collaboration, CMS-PAS-EXO-14-007, http://cds.cern.ch/record/2206863.
18. ATLAS Collaboration, ATLAS-CONF-2017-016, http://cds.cern.ch/record/2257952.
19. ATLAS Collaboration, ATLAS-PHYS-PUB-2017-002, http://cds.cern.ch/record/2243753.
20. ATLAS Collaboration, ATLAS-CONF-2016-014, http://cds.cern.ch/record/2141001.
21. CMS Collaboration, CMS-PAS-B2G-16-002, http://cds.cern.ch/record/2141070.
22. CMS Collaboration, arXiv:1701.08328, submitted to *Phys. Lett.* B; CMS Collaboration, arXiv:1701.07409, submitted to *JHEP*; CMS Collaboration, arXiv:1612.00999, submitted to *Phys. Lett.* B.