The experimental status of direct searches for exotic physics beyond the standard model at the Large Hadron Collider

Salvatore Rappoccio

University at Buffalo, State University of New York, 239 Fronczak Hall, Amherst, NY, USA 14260

Abstract
The standard model of particle physics is an extremely successful theory of fundamental interactions, but it has many known limitations. It is therefore widely believed to be an effective field theory that describes interactions near the TeV scale. A plethora of strategies exist to extend the standard model, many of which contain predictions of new particles or dynamics that could manifest in proton-proton collisions at the Large Hadron Collider (LHC). As of now, none have been observed, and much of the available phase space for natural solutions to outstanding problems is excluded. If new physics exists, it is therefore either heavy (i.e. slightly above the reach of current searches) or hidden (i.e. currently indistinguishable from standard model backgrounds). We summarize the existing searches, and discuss future directions at the LHC.

Keywords: Beyond standard model; BSM; Exotica; EXO; B2G; LHC; CERN;

1. Introduction
A man said to the universe:
"Sir, I exist!"
"However," replied the universe,
"The fact has not created in me
A sense of obligation."
– Stephen Crane

Particle physics is at a crossroads. The standard model (SM) explains a wide range of phenomena spanning interactions over many orders of magnitude, yet no demonstrated explanation exists for a variety of fundamental questions. Most recently, the discovery of the Higgs boson \[1, 2, 3, 4, 5, 6, 7, 8, 9\] at the ATLAS \[10\] and CMS \[11\] detectors has elucidated the mechanism of electroweak symmetry breaking, but there is no explanation for why the scale of its mass is so much different from naive quantum-mechanical expectations (the “hierarchy problem”) \[12, 13, 14, 15, 16, 17, 18, 19, 20\]. Dark matter (DM) remains an enigma, despite extensive astronomical confirmation of its existence \[21, 22, 23\]. Neutrino masses are observed to be nonzero \[24, 25, 26, 27\], and elements of the PontecorvoMakiNakagawaSakata matrix \[28, 29\] have been measured, but these masses are not easily accounted for in the SM \[30\]. Unification of the strong and electroweak forces is expected, but not yet observed nor understood \[31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44\]; such models often predict the existence of yet-to-be-observed leptoquarks (LQs) or proton decay \[45\]. Furthermore, there are unexpected observations that are not explained in
the SM, such as the baryon asymmetry [46], anomalies in the decays of bottom-quark hadrons [47], a discrepancy in the anomalous magnetic moment of the muon \((g-2)\) [48], and the strong CP problem [49, 50, 51]. Even further, there are open questions about long-standing observations, such as whether or not there is an extended Higgs sector [52], why there are multiple generations of fermions with a large mass hierarchy [32, 53, 54, 55], and why no magnetic monopoles are observed to exist [56]. For these reasons, the SM is considered to be an effective field theory, and that physics beyond the SM (BSM) should exist.

In this Review, we will (non-exhaustively) discuss a subset of these questions that have been investigated recently at the LHC with 13 TeV proton-proton collisions by the ATLAS, CMS, and LHCb [57] experiments. From a collider standpoint, we will discuss the solution to the hierarchy problem, dark matter, the origins of neutrino masses, unification, and compositeness. We will also discuss the possibilities for improvements of these searches at the High-Luminosity LHC (HL-LHC) or other future colliders.

One very popular group of theories to explain several of these phenomena involve supersymmetric (SUSY) extensions to the SM [12, 13]. With a few exceptions, this Review will focus on answers to the above questions that do not involve SUSY, although it remains a theoretically attractive solution. This Review will also primarily not focus on solutions that involve an extended Higgs sector, nor open anomalies in hadron spectroscopy.

Many models of BSM physics that can be tested at the LHC involve spectacular signatures that distinguish them from SM backgrounds. It is therefore worthwhile to discuss the searches for new physics with their unique signatures in mind. As such, we will first broadly discuss the signatures used for LHC BSM searches, and then discuss the implications on various scenarios.

The rest of this Review will be structured as follows. We discuss novel reconstruction techniques that are used extensively in searches in Sec. 2 solutions to the hierarchy problem in Sec. 3 searches for DM in Sec. 4 understanding the neutrino mass in Sec. 5 the unification of the forces (including leptoquarks) in Sec. 6 and finally the compositeness of the fundamental particles in Sec. 7. As a guide, Figs. 1-7 show the summaries of the searches for non-SUSY BSM physics at ATLAS and CMS reconstructed with the various techniques outlined in Sec. 2.

2. Tools of searches for BSM physics

Overall, the major signatures of the searches for BSM physics will include: (1) traditional signatures involving leptons, jets, and photons with high transverse momentum \((p_T)\), or missing transverse momentum \((p_T^\ell)\); (2) signatures involving particles that have lifetimes long enough to detect their decays (“long-lived particles”); (3) signatures with highly Lorentz-boosted SM particles that result in collimated, massive jets (“boosted hadronic jets”); and (4) signatures that decay to lower-mass states, which must be Lorentz-boosted via initial-state radiation (ISR) to be detected (“ISR boosted”).

2.1. Traditional signatures

The ATLAS and CMS experiments have been designed primarily with traditional signatures for particle collisions in mind, with relatively prompt signals containing hadrons and isolated leptons or photons. The LHCb experiment has slightly different goals, i.e. to precisely measure bottom and charm hadron production, decays, and properties, as well as other particles with long lifetimes. Of course, many models of new physics manifest in SM-like signatures with different kinematic decays, or at different rates, compared with their SM counterparts. Considerable effort must occur to ensure optimal performance of the detectors, triggers, object reconstruction, calibration, etc. A thorough discussion of the experimental challenges facing the LHC experiments is beyond the scope of this paper, however we will highlight a few key ideas that are used in searches for BSM physics that look qualitatively similar to SM production.

Hadronic jets are the result of fragmentation and hadronization of the underlying quarks and gluons in the LHC interactions. Due to the confinement and asymptotic freedom of the quantum chromodynamic (QCD) interaction,
### ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

| Model | $f, y$ | Jets† | $E_{T}^{miss}$ | $|\mathcal{L}|$ unit | Limit |
|-------|--------|-------|----------------|-----------------|-------|
| AOD $G_{L} \rightarrow g/\gamma$ | $0, 1 \rightarrow 4, 4$ | Yes | 36.1 | 1.8 TeV | $\sim 1.4$ |
| AOD non-resonant $y \gamma$ | $2, 2 \rightarrow 4, 4$ | Yes | 36.7 | 2.3 TeV | $\sim 1.4$ |
| AOD $Q_{R}$ | $2, 2 \rightarrow 4, 4$ | Yes | 37.8 | 3.0 TeV | $\sim 1.4$ |
| AOD D$^{*}$ high $2, y$ | $2, 2 \rightarrow 4, 4$ | Yes | 3.2 | 3.0 TeV | $\sim 1.4$ |
| AOD D$^{*}$ multijet | $2, 2 \rightarrow 4, 4$ | Yes | 3.6 | 3.0 TeV | $\sim 1.4$ |
| RSI $G_{L} \rightarrow y \gamma$ | $2, 2 \rightarrow 4, 4$ | Yes | 37.8 | 3.3 TeV | $\sim 1.4$ |
| Bulk RS $G_{L} \rightarrow WW/ZZ$ | multi-channel | Yes | 36.3 | 3.5 TeV | $\sim 1.4$ |
| Bulk RS $G_{L} \rightarrow tt$ | $1, 2 \rightarrow 4, 4, 4$ | Yes | 36.1 | 3.5 TeV | $\sim 1.4$ |
| Bulk RS $G_{L} \rightarrow t\bar{t}$ | $1, 2 \rightarrow 4, 4, 4$ | Yes | 36.1 | 3.0 TeV | $\sim 1.4$ |

| Model | $f, y$ | Jets† | $E_{T}^{miss}$ | $|\mathcal{L}|$ unit | Limit |
|-------|--------|-------|----------------|-----------------|-------|
| Gauge bosons | | | | | |
| SM $Z' \rightarrow tt$ | $2, 2 \rightarrow 4, 4$ | Yes | 36.1 | 3.0 TeV | $\sim 1.4$ |
| SM $Z' \rightarrow tt$ | $2, 2 \rightarrow 4, 4$ | Yes | 36.1 | 3.0 TeV | $\sim 1.4$ |
| SM $W' \rightarrow tt$ | $2, 2 \rightarrow 4, 4$ | Yes | 36.1 | 3.0 TeV | $\sim 1.4$ |
| HVT $W' \rightarrow WW \rightarrow eee$ | multi-channel | Yes | 36.1 | 3.5 TeV | $\sim 1.4$ |
| HVT $W' \rightarrow WW \rightarrow eee$ | multi-channel | Yes | 36.1 | 3.5 TeV | $\sim 1.4$ |

| Model | $f, y$ | Jets† | $E_{T}^{miss}$ | $|\mathcal{L}|$ unit | Limit |
|-------|--------|-------|----------------|-----------------|-------|
| Other | | | | | |
| LRSM Majorana $\nu$ | $2, 2 \rightarrow 4, 4$ | Yes | 36.3 | 3.5 TeV | $\sim 1.4$ |
| Higgs triplet $H^{*} \rightarrow WW$ | multi-channel | Yes | 36.1 | 3.5 TeV | $\sim 1.4$ |
| Mixing (non-resonant) | $1, 1 \rightarrow 4, 4$ | Yes | 36.3 | 3.5 TeV | $\sim 1.4$ |
| Multi-charged particles | | | | | |

*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter $j$ (J).
Figure 2: Summary of exotica searches at CMS with traditional and ISR-boosted reconstructed techniques.
Figure 3: Summary of exotica searches at CMS with boosted reconstructed techniques.

Vector-like quark pair production

Vector-like quark single production

Resonances to heavy quarks

Excited quarks

Resonances to dibosons

Leptoquarks

B2G

new physics searches with heavy SM particles
**Figure 4: Summary of long-lived exotica at ATLAS.**

### ATLAS Long-lived Particle Searches* - 95% CL Exclusion

**Status:** July 2018

\[
\int \mathcal{L} \, dt = (3.2 - 36.1) \text{ fb}^{-1} \quad \sqrt{s} = 8, 13 \text{ TeV}
\]

| Model | Signature | \( \mathcal{L} \) at (fb\(^{-1}\)) | Lifetime limit | \( \mathcal{L} \) (fb\(^{-1}\)) | Reference |
|-------|-----------|-----------------|----------------|-------|------------------|
| SUSY  | FPV \( \chi^\pm \rightarrow e\nu/\mu\nu/\nu\nu \) | displaced lepton pair | 20.3 | \( \leq 0.04 \) | 8, 13 TeV | 1504.01562 |
| AMSB  | GGM \( \chi^0 \rightarrow Z \chi_1^0 \) | displaced dimuon | 32.9 | \( \leq 0.1 \) | 8, 13 TeV | 1504.01562 |
| GGM   | non-pointing or delayed \( Z \) | displaced dimuon | 32.9 | \( \leq 0.2 \times 10^{-9} \) | 8, 13 TeV | CERN-EP-2018-173 |
| AMSB  | \( \chi^0 \rightarrow Z \chi_1^0 \) | non-pointing or delayed \( Z \) | 32.9 | \( \leq 0.2 \times 10^{-9} \) | 8, 13 TeV | 1433.0542 |
| AMSB  | \( \chi^0 \rightarrow Z \chi_1^0 \) | non-pointing or delayed \( Z \) | 32.9 | \( \leq 0.2 \times 10^{-9} \) | 8, 13 TeV | 1319.0675 |
| AMSB  | Split SUSY | displaced dimuon | 32.9 | \( \leq 0.3 \times 10^{-9} \) | 8, 13 TeV | 1712.02118 |
| SUSY  | 

### Other

\[ \gamma \ell \ell, e^{\pm} \rightarrow q_{1,2}, v_1, Z_{1,2} \]
Figure 5: Summary of long-lived exotica searches at CMS.

| System                      | Mass Range (GeV) | 95% CL Exclusion on lifetime (µ) | Additional Details                                      |
|-----------------------------|------------------|----------------------------------|--------------------------------------------------------|
| RPV SUSY, μ → τ, m(μ) = 420 | 1                | 8 TeV, 19.7 fb⁻¹ (displaced leptons) |
| τ → τ, m(τ) = 5              | 2                | 8 TeV, 19.6 fb⁻¹ (displaced leptons) |
| H → XX (10%), X → ee, m(H) = 125 | 3                | 8 TeV, 19.6 fb⁻¹ (displaced leptons) |
| GMSB SP8, Z⁺ → γ γ, m(Z⁺) = 250 | 4                | 8 TeV, 19.6 fb⁻¹ (displaced leptons) |
| RPV SUSY, m(μ) = 1000        | 5                | 8 TeV, 19.5 fb⁻¹ (displaced dijets) |
| RPM SUSY, m(μ) = 1000        | 6                | 8 TeV, 19.5 fb⁻¹ (displaced dijets) |
| AMSB ZZ⁺ → γ γ, m(Z⁺) = 200  | 7                | 8 TeV, 19.5 fb⁻¹ (disappearing tracks) |
| AMSB Z⁺ → ℓ⁺ν, m(Z⁺) = 1000 | 8                | 8 TeV, 18.6 fb⁻¹ (stopped particle) |
| GMSB SP8, Z⁺ → γ γ, m(Z⁺) = 250 | 9                | 8 TeV, 19.6 fb⁻¹ (displaced leptons) |
| AMSB Z⁺ → ℓ⁺ν, m(Z⁺) = 200   | 10               | 8 TeV, 18.8 fb⁻¹ (tracker + TOF) |
| AMSB Z⁺ → ℓ⁺ν, m(Z⁺) = 200   | 11               | 8 TeV, 18.8 fb⁻¹ (tracker + TOF) |

**CMS long-lived particle searches, lifetime exclusions at 95% CL**

| System                      | Mass Range (GeV) | 95% CL Exclusion on lifetime (µ) | Additional Details                                      |
|-----------------------------|------------------|----------------------------------|--------------------------------------------------------|
| RPV SUSY, μ → τ, m(μ) = 420 | 1                |                                 |                                                        |
| τ → τ, m(τ) = 5              | 2                |                                 |                                                        |
| H → XX (10%), X → ee, m(H) = 125 | 3                |                                 |                                                        |
| GMSB SP8, Z⁺ → γ γ, m(Z⁺) = 250 | 4                |                                 |                                                        |
| RPV SUSY, m(μ) = 1000        | 5                |                                 |                                                        |
| RPM SUSY, m(μ) = 1000        | 6                |                                 |                                                        |
| AMSB ZZ⁺ → γ γ, m(Z⁺) = 200  | 7                |                                 |                                                        |
| AMSB Z⁺ → ℓ⁺ν, m(Z⁺) = 1000 | 8                |                                 |                                                        |
| GMSB SP8, Z⁺ → γ γ, m(Z⁺) = 250 | 9                |                                 |                                                        |
| AMSB Z⁺ → ℓ⁺ν, m(Z⁺) = 200   | 10               |                                 |                                                        |
| AMSB Z⁺ → ℓ⁺ν, m(Z⁺) = 200   | 11               |                                 |                                                        |

CMS long-lived particle searches, lifetime exclusions at 95% CL.
Figure 6: Summary of searches for DM from multijet final states with an axial-vector mediator at ATLAS.
Figure 7: Summary of searches for DM from multijet final states with an axial-vector mediator at CMS.

CMS Preliminary

Axial-vector mediator
Dirac DM
\( g_{DM} = 1.0 \)
\( g_q = 0.25 \)
\( g_l = 0 \)

LHCP 2017

Exclusion at 95% CL

\[ \text{Observed} \]
\[ \text{Expected} \]

\[ \text{DM} + \gamma (35.9 \text{ fb}^{-1}) \]
[EXO-16-052]

\[ \text{DM} + Z(ll) (35.9 \text{ fb}^{-1}) \]
[EXO-16-048]

\[ \text{DM} + \gamma (12.9 \text{ fb}^{-1}) \]
[EXO-16-039]

\[ \text{Dijet} (35.9 \text{ fb}^{-1}) \]
[EXO-16-056]

\[ \text{Boosted dijet} (35.9 \text{ fb}^{-1}) \]
[EXO-17-001]

\[ \text{DM} \]
the fragmentation and hadronization occur primarily in a collimated spray of particles called “jets”\cite{58}. They are reconstructed from different inputs depending on the detector using the \texttt{fastjet} software package\cite{59,60}. The ATLAS collaboration utilizes primarily topological clustering of their calorimeter deposits (TC)\cite{61}, or occasionally a full reconstruction of the particle flow throughout the detectors (PF)\cite{62}, while CMS utilizes PF almost exclusively except where noted \cite{63}. The typical momentum resolutions and scale uncertainties achieved for both experiments are $\sim 10\%$ and $\sim 0.5\text{--}1.0\%$, respectively, for $p_T = 100$ GeV\cite{64,62,65}. Jets containing bottom or charm hadrons can have some displaced particles within them, and ATLAS, CMS, and LHCb are able to discern very small displacements (a few tens of microns) with respect to the beam axis with dedicated tagging algorithms\cite{66,67}. This allows the reconstruction of vertices a few hundred microns from the beam axis. Such information can be used to efficiently discriminate jets that originate from bottom or charm quarks from those that originate from lighter quarks or gluons.

Electrons and photons are reconstructed in both experiments accounting for interactions with the material of the detector using dedicated algorithms\cite{68,69,70,71}, and uses the electromagnetic calorimeter and tracking information. Muons are reconstructed using dedicated detectors outside of the calorimeter structures\cite{72,73}, as well as information about the muon track and the ionization deposits in the calorimeters. The performance is dependent on the purity of the signal in question, but a good benchmark is the performance in reconstruction of electrons from $Z$ bosons, where the experiments achieve electron momentum resolutions and scale uncertainties around $1\%$ and $1\text{--}2\%$, respectively, and muon momentum resolutions and scale uncertainties around $1\%$ and $1\text{--}2\%$, respectively.

The reconstruction of $\tau$ leptons is performed using jets as inputs, then applying selection criteria consistent with individual particle signatures that take advantage of the unique decays of the $\tau$ lepton either hadronically to one or three pions, or semileptonically to lighter leptons and neutrinos\cite{74,75}. There is an additional challenge in $\tau$ reconstruction, in that there are neutrinos produced in their decay that escape detection, which causes difficulties in reconstruction of the four-vector. The momentum resolutions and scale uncertainties are around $15\%$ and $0.5\text{--}1.0\%$ for $\tau$ leptons decaying from $Z$ bosons, respectively.

Neutrinos are produced at the LHC primarily through weak interactions of the $W$ boson. They can be produced directly through on-shell $W$ decays, or indirectly via weak decays of bottom or charm quarks, or $\tau$ leptons. Neutrinos are not directly detected. Their presence is inferred by taking advantage of the fact that, since the proton beams carry minimal transverse momentum, the vector sum of the transverse momenta of all of the observed particles should cancel. This is referred to as a “transverse momentum imbalance” or “missing transverse momentum” $p_T^\perp$. This technique can also be used to signal the presence of other particles that are not directly detected, such as DM or other exotic particles. A critical feature of this method of detection is to have nearly hermetic coverage of the phase space, but perfect coverage is unrealistic. This incomplete coverage in part contributes to the $p_T^\perp$ resolution, which is around $10\text{--}15\%$ in control samples involving $Z$ boson decays to $e^+e^-$ and $\mu^+\mu^-$. 

## 2.2. Long-lived particles

It is possible for some particles that are produced in the collision to decay after traveling a relatively long distance. The most colloquially well-known particles in this category are muons and pions, as produced copiously via interactions of cosmic rays with the upper atmosphere. The mechanics behind such long decay times can differ, but broadly, there is either a massive force mediator (such as the $W$ boson) that weakens the interaction strength, or the masses of the parent and child particles in the decay are so close that the kinematic phase space for the decay is restricted. In either of these cases, the probability for the particle to decay at a given time is reduced, causing a longer lifetime.

The LHC detectors were not originally intended to detect particles that decay further than a few centimeters from the beamline. The focus has traditionally been on detecting jets containing bottom or charm quarks, which decay a few hundred micrometers from the beam axis. Most other particles are considered to be effectively stable.
on the timescales via which they traverse the detectors. For instance, accounting for their Lorentz boosts, both pions and muons are long-lived enough to avoid decaying within the detector itself.

However, considerable progress has also been made to detect particles with intermediate lifetimes (longer than bottom and charm hadrons, shorter than pions and muons). There are several strategies that can be employed here. We discuss a few non-exhaustively. Firstly, the same strategy as the bottom and charm hadron detection can be used, whereby particles with long lifetimes will have large impact parameters with respect to the beam axis. For instance, in Refs. [76, 77], the detectors can discern particles that decay tens of millimeters away from the beam axis. Secondly, signals of events in the calorimeters that occur outside the beam crossing can be used as in Ref. [78]. In this case, particles may be produced with long enough lifetimes to be trapped by the nuclear material of the hadronic calorimeter, to decay some time later. Thirdly, the particles may be heavy and quasi-stable, leaving large amounts of ionizing radiation in the tracking detectors.

Newer ideas include proposals of dedicated satellite experiments outside of the detector collision halls, such as the “MAssive Timing Hodoscope for Ultra Stable neutraL pArticles” (MATHUSLA) detector [79, 80], which will be able to detect particles produced in LHC collisions that decay several hundred meters from the interaction point, which is the same scale as limits from Big Bang Nucleosynthesis (BBN). Such satellite experiments show strong promise in extending the reach of discovery of new particles with long lifetimes.

2.3. Boosted hadronic jets

Particles with masses above the scale of the SM are widely expected in many BSM scenarios. If these particles have couplings to the heavier SM particles (and they must, if we are to produce them at the LHC), then often they contain couplings to top quarks and W/Z/H bosons. In these cases, due to the large difference in masses between the BSM particle and the SM particles, the latter will be produced with large Lorentz boosts. This causes the decay products of the unstable SM particles to be highly collimated. We refer to these as “boosted objects” [81, 82, 83, 84, 85, 86].

In the case of particles that decay fully leptonically such as $Z \rightarrow \ell^+\ell^-$, there are some modest adjustments to identification criteria that distinguish this case from traditional reconstruction techniques in Sec. 2.1. These involve nonstandard reconstruction techniques to ensure that isolation requirements are relaxed, since the resulting leptons typically appear geometrically close to other objects.

Particles that decay hadronically (such as $H \rightarrow bb$ or $t \rightarrow Wb \rightarrow q\bar{q}b$) or semileptonically (such as $t \rightarrow Wb \rightarrow l\nu b$) pose more of a challenge. The reason is that hadronic particles, as mentioned in Sec. 2.1, already tend to fragment and hadronize in regions with small spatial extent. As such, the signatures of boosted hadronically decaying particles can look quite similar to traditional jets. Special techniques involving the substructure of jets have been developed to distinguish boosted hadronically decaying particles from standard jets.

Since these techniques are somewhat novel, the full phase space of possibility has not yet been explored for performance improvements. Some advances can come from better theoretical understanding of the underlying radiation patterns of jets, and/or from new advances in machine learning to better distinguish various types of jets [86].

2.4. ISR-boosted particles

Oftentimes, particles can be created that create no detector signature (such as neutrinos or DM) or signatures that are completely overwhelmed by SM backgrounds (such as hadronic decays of the W or Z bosons). Reconstruction of such particles is impossible with standard techniques at the LHC.

In order to solve this problem, one clever idea is to look for signatures that recoil against initial-state radiation particles such as gluons. With sufficient Lorentz boosts, the previously undetectable or indiscernible particles become accessible again. This is the strategy behind most of the searches for DM outlined below, as well as searches for hadronically decaying BSM particles with masses below the $W/Z/H$ boson masses. This is also the
strategy behind the recent observation of $H \rightarrow b \bar{b}$ \cite{77,88}, and the observation of hadronic decays of the $W$ and $Z$ bosons while searching for lower-mass vector resonances in Ref. \cite{89}.

3. The hierarchy problem

The hierarchy problem is, in its simplest form, confusion about why the electroweak scale (100 GeV) is so much different from the Planck scale ($10^{18}$ GeV). There are many references that describe this in detail (for instance, Refs. \cite{12,90}), so here we discuss only the broadest overview.

The Higgs potential can be written as

$$V = m_H^2 |H|^2 + \lambda |H|^4.$$  \hspace{1cm} (1)

where $V$ is the Higgs potential, $H$ is the Higgs field, $m_H$ is the MS mass of the Higgs boson, and $\lambda$ is a free parameter, experimentally determined by the vacuum expectation value (vev). The vev is nonzero if $\lambda > 0$ and $m_H^2 < 0$, resulting in $\langle H \rangle = \sqrt{-m_H^2}/2\lambda$, where $\langle H \rangle = 174$ GeV and the observed Higgs mass is around 125 GeV, yielding $m_H^2 = -(92.9 \text{ GeV})^2$.

The issue arises when one considers couplings of the Higgs field to SM fermions such as the top quark, in Fig. 8. These diagrams result in higher-order corrections to $m_H$ such as

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{UV}^2 + \ldots,$$  \hspace{1cm} (2)

where $\lambda_f$ is the Yukawa coupling of the fermion $f$ to the Higgs field, and $\Lambda_{UV}$ is some upper cutoff of the integral to yield a finite result. There is no physical mechanism within the SM itself to yield a small value of $\Lambda_{UV}$ to arrive at the observed Higgs boson mass, so either the SM is valid up to the Planck scale (resulting in $\Lambda_{UV} = \Lambda_{\text{Planck}}$, or a new physical scale exists, $\Lambda_{\text{BSM}}$, between the electroweak and Planck scales, interpreted as the scale of BSM physics.

There are several proposals for the nature of BSM physics to solve the hierarchy problem, including SUSY \cite{12,13}, new strong dynamics or technicolor \cite{14,15}, and extra dimensions, either large \cite{16,19} or warped \cite{17,18}. Production of signatures involving “prompt” SUSY will not be discussed in this Review, although signatures of SUSY with large lifetimes are discussed as they overlap significantly with signatures from other models \cite{92,93}. Large extra dimensions (LED) are discussed below. Strong dynamics and warped extra dimensions are linked by an AdS/CFT correspondence \cite{94}, and are discussed together using the language of extra dimensions.

The solutions to the hierarchy problem and unification (see below) often predict additional gauge bosons. It is often convenient to simply assume SM-like couplings in the “sequential” SM (SSM). These are usually taken as benchmark scenarios and overlap with signatures from other models.
3.1. Large extra dimensions

The existence of large extra dimensions (LED)\[16\, 19\] solves the hierarchy problem by positing that gravity is distributed through a higher-dimensional space (the “bulk”) whereas the SM particles are confined to a subspace (the “SM brane”). This results in a natural value for $\Lambda_{\text{UV}}$, much smaller than $10^{18}$ GeV. The relevant parameters are the number of extra dimensions $n$, the corresponding fundamental Planck scale $M_D$, and the mass threshold $M_{\text{th}}$, above which black holes are formed. The relationship between $M_D$ and the 3-dimensional Planck mass $M_{\text{pl}}$ is given by

$$M_D = \frac{1}{r} \left( \frac{r M_{\text{pl}}}{\sqrt{8\pi}} \right)^{\frac{1}{n+2}}$$  \hspace{1cm} (3)

where $r$ is the compactification radius.

There are many signatures for LED models, including copious production of microscopic black holes\[95\, 96\]. These black holes decay almost instantly into one or more particles at high $p_T$, including signatures with photons, leptons, jets, or $p_T$. This provides a very unique signature at the LHC. For black hole masses far above $M_{\text{th}}$, the semiclassical approximation holds, and the black hole will decay uniformly to all SM particles (with quarks and gluons obtaining an enhancement from their 3 colors). The signature there will be a large number of high-$p_T$ particles, and so the sensitive variable will be the scalar sum of the $p_T$ of all of the jets, leptons, photons, and $p_T$. For black hole masses near $M_{\text{th}}$, however, the semiclassical approximation is invalid, and quantum-mechanical decay to a few highly energetic particles is the dominant decay mode.

At 13 TeV, there have been a large number of searches for such particles at both ATLAS\[97\, 98\, 99\, 100\] and CMS\[101\, 102\, 103\]. Figures 1-3 show the results of many searches involving high-multiplicity events or events with significant $p_T$. The mass limits depend on the signature, the model, and the number of extra dimensions, but are typically between 2-10 TeV. This covers a significant dynamic range of interest for these models for the case of $n = 4$ spatial dimensions, since models with considerably higher masses would be less likely to solve the hierarchy problem naturally.

The energy range of LED models is very large. As such, increases in the center-of-mass energy will provide the strongest improvements in sensitivity. However, better estimation of SM backgrounds can also lead to improvements with more data at the HL-LHC.

3.2. Warped extra dimensions

Extra-dimensional alternatives to LED include the “RS1”\[17\] and “RS2” models\[18\]. The RS1 model hypothesizes compact extra dimensions with two branes, one at the Planck scale and the other at the TeV scale. The SM particles are presumed to exist primarily on the TeV brane, and have Kaluza-Klein (KK) excitations around the TeV scale, which behave similarly to their SM counterparts and hence can be detected at colliders like the LHC. The RS2 model is similar to RS1, but omits the brane at the TeV scale, and also yield a KK tower of particles corresponding to the existing SM particles.

RS1 models can produce black holes as in Sec. 3.1 with

$$M_D = \frac{M_{\text{pl}}}{\sqrt{8\pi}} e^{-\pi k r}$$  \hspace{1cm} (4)

where $r$ and $M_{\text{pl}}$ are defined in Eq. 3 and $k$ is a warp factor. These models also result in KK excitations of the graviton\[104\] and gluon\[105\, 106\], which can yield signatures in many final states such as dibosons, diquarks, di-Higgs, diphotons, and many others. One common feature is the high masses of the KK excitations, which often subsequently decay to highly Lorentz-boosted SM particles, necessitating the usage of the techniques outlined in Sec. 2.3. Such models also can result in additional quarks and/or leptons that transform as vectors under the ordinary symmetry of the SM, referred to as “vector-like” quarks (VLQs) or leptons (VLLs)\[107\].
Typically, the simplest signatures involving RS models (or the SSM) are resonances that decay to two objects. There are dilepton $[108,109,110,111,112,113,114]$, diphoton $[115,116,117,118,119]$, jet+boson or diboson $[120,121,122,108,123,109,124,125,126,127,128,129,130,131,132,133,134,135,122,136,137,138,139,140,141,142,143]$, and diquark/dijet $[144,145,146,144,147,148,149,150]$ analyses. There are also specialized diquark/dijet analyses in resonant production of $b\bar{b}$ $[151,152]$, $tt$ $[123,153,154]$, $tb$ $[155,156,157]$, and resonances decaying to VLQs $[158]$. Overall, the benchmarks used in these searches are RS1 KK gravitons, RS1 KK gluons (for $tt$ resonances), or $W'$ bosons (for $tb$ resonances). There are also other models that are probed with the dijet and $b\bar{b}$ resonance papers. The limits on these models are already quite stringent, effectively saturating the available parton luminosity at high masses in the multiple TeV range. There are also analyses that manifest as a combination of ISR boosts as in Sec. 2.4 and boosted hadronic jets as in Sec. 2.3, shown in Ref. [89]. There are also many analyses searching for direct production of VLQs $[159,160,161,162,163,164,111,166,167,168,169]$. Updates to these analyses will need to predominantly start focusing on reducing the SM background and its uncertainty, until a new collider is built at a significantly higher energy. In many cases, the resonances at higher masses are so broad that they are predominantly produced away from the resonant peak (“off-shell”), and manifest like a contact interaction above the SM backgrounds. In the case of a signal at lower mass, it will be difficult to interpret the precise mass of the new physics signals because of this off-shell effect. There is still sensitivity in the lower-mass states with increasing luminosity, so the HL-LHC will continue to provide useful improvements in these searches.

4. Dark matter

Dark matter comprises 4-5 times as much of the universe as ordinary matter. It is natural to suppose that DM is comprised of particles that interact very seldomly, i.e. that it is due to “weakly interacting massive particles,” or WIMP. The relic density of DM hints at particle DM at the electroweak scale (the “WIMP miracle”) $[21,22,23]$. However, as of now, we have no candidate particle to explain the evidence. This remains one of the major open questions in physics.

There is no shortage of models to explain the elusive phenomenon, with varying degrees of complexity and explanatory power. Many SUSY models contain a particle that only interacts very weakly with ordinary matter (the “lightest SUSY particle”, or LSP), providing a simple DM candidate. At the same time, many such models also attempt to address questions about the hierarchy problem, the nature of space-time, grand unified theories, and even string theory. For this reason, SUSY has long been held as the most attractive solution to the question of DM, because it can explain a wide range of phenomena with simple assumptions.

Unfortunately, as of yet, no easily detectable signals have been observed at the LHC. This, in and of itself, is not necessarily a problem, because the scale of SUSY could always be much heavier than we can currently access, or exists in a region where the signals are hidden among SM backgrounds. The former case, however, limits the ability for SUSY to mitigate the hierarchy problem. The infrared divergences of the mass of the Higgs boson are only canceled if the masses of the SUSY particles are very close to their SM counterparts. This raises questions of whether or not the models themselves “naturally” explain the hierarchy problem. For the case of subtle signatures, of course, such questions of naturalness are less pressing, and can still preserve solutions to the hierarchy problem with a DM candidate. Despite those attractive theoretical features, there is really no a priori reason (other than our personal aesthetic) that one model should address all of these open questions simultaneously. As mentioned above, this review will not discuss the overall state of the search for SUSY, leaving this to other reviews, but instead we will focus on specific SUSY-inspired final states that include signatures that are difficult to detect (“hidden”).

While SUSY does provide a single natural DM candidate, there is nothing constraining the particle content of the dark sector. There may be a family of dark particles, even with their own interactions, that comprise the dark sector. The only real constraint we have is that if WIMPs exist, they interact weakly with SM particles. For
this reason, more model-agnostic searches have become popular, with the help of effective field theories (EFTs) or simplified models of DM interactions \[170\]. These focus more on the signatures involving DM and place constraints simultaneously on the masses of the DM, and the mediator via which they interact with the SM particles. An exhaustive list of final states with spin hypotheses of the mediator can thus be made, and an extensive program has been undertaken to investigate these models.

We will now investigate the phenomenology of hidden signatures, as well as that of EFTs/simplified models in detail.

4.1. Hidden sectors and RPV SUSY

The postulation of a hidden sector \[171, 172, 29\] can explain DM, and arises in many solutions to the hierarchy problem. Some models postulate a non-abelian sector of light particles that interacts with the SM via a heavy mediator, thus becoming “hidden” or “dark”. These particles could form complex bound states since they are strongly interacting, thus forming “valley hadrons” or “v-hadrons” analogous to QCD. The LHC could in principle produce these v-hadrons, which would subsequently decay to detectable SM particles through the massive mediators after a long time \[173\], resulting in observable SM particles that are displaced from the interaction point, analogous to a charged pion that decays to a muon and neutrino via a massive W boson. This necessitates utilizing the detection techniques outlined in Sec. 2.2. Furthermore, the decay products may also potentially be collimated, necessitating the techniques outlined in Sec. 2.3. The Higgs boson could in principle couple with the hidden sector, providing a “Higgs portal” \[174\]. The latter signature would be a Higgs boson produced and decaying into long-lived v-hadrons, which may or may not decay to SM particles within the detector acceptance.

In addition to model-agnostic hidden sectors, SUSY can result in signatures that are quite similar, if they violate R-parity \[92, 93\], i.e. RPV SUSY. In these cases, the LSP will often be sufficiently long-lived to decay centimeters or meters away from the LHC collisions. The methodologies for detection can range from detection of particles that decay within the tracker volume, possibly with other distinguishing features like \(p_T\) \[175, 77, 76\], those that contain extensive ionizing radiation in the tracker \[176\], particles that decay into hadronizing particles far from the interaction region (“emerging” jets) \[177\], particles that get trapped in the nuclear material and subsequently decay \[78\], particles that decay to unobservable particles in flight (“disappearing” tracks”) \[178\], and others not discussed here.

Figures 4 and 5 show summary plots from ATLAS and CMS of searches for long-lived signatures from various models. An impressive array of models has been investigated at a wide range of distances over 15 orders of magnitude, ranging from millimeters to many meters at very long times.

Future directions of these searches will predominantly involve extending the baseline of detection or searches. Projects such as MATHUSLA are extremely promising ways to extend the reach and capability of these types of searches. It is still quite possible that natural SUSY models (RPV or not) could be found in these difficult signatures, and it should be a major part of the HEP program in the future.

4.2. EFTs and simplified models of DM

The overall construction of an EFT involving DM postulates a very massive mediator of the interaction between DM and SM particles, and hence can be modeled as a contact interaction. Simplified models, on the other hand, postulate various DM–SM mediators, as well as a DM particle, all with varying spins and couplings to the SM particles. Broadly speaking, these can both result in similar signatures. Overall, since any DM particles that are produced in LHC collisions will not interact with the detectors at all, detection techniques focus primarily on ISR-boosted detection techniques as in Sec. 2.4 and reconstruct the observable interaction from ISR with traditional techniques as in Sec. 2.1 or with boosted hadronic jets as in Sec. 2.3. Depending on the final state, flavor tagging techniques to detect bottom or top quarks can also be used. As such, existing analyses include a dizzying array of final states \[179, 180, 132, 181, 182, 183, 184, 185, 147, 186, 187, 188, 189, 190, 149, 150\]. These are usually
colloquially referred to as “mono-X” searches, since the signature in the detector is a single particle (X) recoiling against the DM particle. The particle X can be any SM particle. There are therefore searches with signatures of mono-jet, mono-bottom-jet, mono-top-jet, mono-photon, mono-W, mono-Z, mono-Higgs, etc. The mediators can also interact with a pair of particles, so signatures can also involve $q\bar{q}$, $\ell^+\ell^-$, $b\bar{b}$, $t\bar{t}$, etc.

Various interaction hypotheses are investigated for the DM–SM mediators. They can be vectors, axial-vectors, scalars, or pseudoscalars. The coupling constants for the DM–SM interaction are also unconstrained, so results must be framed in terms of these parameters. For instance, Ref. [103] present limits on the masses of a vector mediator and DM (with couplings to SM quarks equal to 0.25) of 1.8 and 0.7 TeV, respectively, in signatures containing Lorentz-boosted $V \rightarrow q\bar{q}$. Another example is Ref. [185], which presents limits on the masses of an axial-vector mediator and DM of 1.5 and 0.4 TeV, respectively, using a mono-jet signature.

In simple interpretations of the DM–nucleon scattering cross section as a function of the DM mass, LHC searches complement direct detection (DD) and indirect detection (ID) searches [191]. Overall, LHC searches are more sensitive at very low mediator masses, as well as for axial-vector mediators, whereas ID/DD searches are more sensitive at higher masses if there are vector or scalar mediators. For instance, for a vector mediator, Refs. [103] [185] show DM–nucleon cross-section limits of $\sim 10^{-42}$ cm$^2$ for a DM mass of 1 GeV, whereas there is no corresponding DD sensitivity, but the DD searches become more sensitive for DM masses around 30 GeV, with cross-section limits of $\sim 10^{-46}$ cm$^2$ from XENON1T [192]. Figures 6 and 7 show limits of searches for axial-vector-mediated DM in multijet final states from ATLAS and CMS, respectively.

For much of the phase space, the limits can be improved with increased luminosity. As such, future prospects for DM detection are quite strong at the HL-LHC.

5. Neutrino mass

As of yet, the observation of non-zero neutrino masses is the strongest direct evidence for BSM particle physics. DM also strongly points to a new sector, but has not been directly observed nor produced in particle-particle interactions, and the effects are only observed at large distances, either in galaxial rotations or CMB observations. Neutrinos, on the other hand, have been directly shown to have individual masses, and an extensive research program exists to investigate this regime [193].

The LHC can play a role in the investigation of such anomalies by searching for possible heavy partners of the neutrino $N$, which are naturally predicted by the “seesaw” mechanism [194] [195] [196] [197], where the neutrino masses $m_\nu$ are proportional to $y^2_\nu v^2/m_N$, where $v$ is the vacuum expectation value of the Higgs field, and $y_\nu$ is a Yukawa coupling. Very small neutrino masses $m_\nu$ could correspond to large masses for the heavy neutrinos. It is quite reasonable to expect that, should such a mechanism exist, the LHC would be able to observe these partners. There are, as such, many searches for BSM physics involving heavy neutrinos decaying into various final states, including leptons, jets, or bosons [161] [198] [137] [199] [200].

Overall, the exclusion depends on the relative mixing between the light and heavy neutrinos, $V_{\nu N}$. If this mixing is 0.1, the masses probed by existing searches are in the several hundred GeV range. If the mixing is 1, the masses probed are close to 1 TeV. Production of heavy neutrinos is mostly limited by the available center-of-mass energy, so future colliders will be very effective at extending the reach of searches for heavy neutrinos. There will be, however, still available phase space to explore at the HL-LHC for lower masses.

6. Unification

Extensions to new gauge sectors that encompass the SM have long sought to find an overarching symmetry that couples the strong and electroweak forces. Fundamentally, any unification of the strong and electroweak forces will
involve some BSM coupling between quarks and leptons. One can think of this as lepton number being a fourth color. Oftentimes, such an interaction will contain new particles that contain quantum numbers for both the strong and electroweak forces. These are known as “leptoquarks” (LQs) \[31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44\]. Of course, such interactions would also contain predictions for unstable protons \[45\], where extremely stringent limits must be considered in building BSM physics models.

There is further recent interest in LQs because they have been proposed as solutions \[201, 202, 203, 204, 205, 206, 207, 208\] to several outstanding hints of lepton flavor non-universality in heavy-flavor hadron observations from Belle \[209\] and LHCb \[210, 211, 212\]. Such particles have also been hypothesized \[213, 214\] to explain the $g - 2$ anomaly \[48, 215\].

With those considerations in mind, one of the most likely observable consequences for unification at the LHC will be in searches for LQs. Broadly speaking, these will occur as an excess of events involving both leptons and hadrons. There are various strategies to deal with such signatures \[216, 217, 163, 137, 199, 218, 216\]. One example is to search for first- or second-generation LQs coupling to first- or second-generation quarks and leptons. In those cases, analyses can use the known rates of electroweak production of $W$ and $Z$ bosons, as well as top quark pair production, to predict the background for other more massive states that involve similar signatures. Another strategy is to search for third-generation LQs in signatures involving $\tau$ leptons, bottom or top quarks. The SM backgrounds for such signatures are dominated by top quark pair production, which can be predicted. The limits for LQs are currently on the order of 800-1500 GeV depending on the channel.

Since the masses of the LQs are relatively modest, increases in luminosity at the HL-LHC can provide a good opportunity to continue these searches.

7. Compositeness

Ever since Rutherford began to probe the structure of the proton, the question of whether or not the particles we observe are fundamental or composite is a perennial question. Investigations of quark compositeness are not fundamentally different than the Rutherford experiment, and involve investigations of the number of high-mass quark-quark interactions. Since a massive mediator would often manifest as a contact interaction at lower energies (much like the $W$ boson appears as a contact interaction in pion decay, etc), the searches often focus on such interactions. At its heart, the LHC is a QCD jet factory. As such, it can set extraordinarily sensitive limits on such fundamental interactions. References \[145, 149, 219\], for instance, are able to set limits between 10-20 TeV. The size of the quark is pointlike down to $10^{-18}$ m, and the scale of contact interactions manifesting in dijet samples must be larger than the scale of the LHC center-of-mass energy.

There are also searches for signals of compositeness that search for excited states of fermions, which then radiate either photons or gluons with specific characteristics. For example, excited quarks are investigated in Refs. \[145, 220, 221, 152, 150\], and dedicated searches for excited top quarks are shown in Ref. \[222\]. Excited top quarks are excluded below 1 TeV, and excited light quarks are excluded below 3-5 TeV.

Generally speaking, compositeness is probed by increases in center-of-mass energy more than by collecting more data. As such, the HL-LHC prospects for such searches for BSM physics are somewhat limited. New colliders at a higher center-of-mass energy would drastically increase the sensitivity.

8. Discussion

As of yet, there are no substantive signals of BSM physics at the LHC. However, it is unwise to conclude that none exist. There is, a priori, no particularly better region of phase space aside from arguments about how much tuning we are psychologically comfortable with in nature. It is indeed true that a great portion of the available kinematic phase space of the LHC has been ruled out for strongly produced BSM signatures, but the new particles
may simply have larger masses than we have excluded at the LHC (i.e. are heavy), or may have cross sections that are below our current sensitivity or decay outside our detector volume (i.e. are hidden). There are multiple strategies to deal with increasing sensitivity to these signatures, based on new detection and reconstruction techniques.

Of course, for heavy signatures, there is nothing better than building a new proton-proton collider at a much higher center-of-mass energy. However, better reconstruction and background rejection techniques can improve sensitivity considerably. In addition, there are a plethora of targeted signatures that are not difficult to investigate, but the LHC experiments have simply not addressed them.

Hidden signatures require several approaches. If a particle is strongly produced, but decays outside of the region where our traditional techniques are efficient, new strategies must be employed to be sensitive to them. This includes detection of long-lived particles via extensions to the CMS and ATLAS detectors such as MATHUSLA. Alternatively, there may be direct signatures that are produced with smaller cross sections than we are currently sensitive to. Such searches will improve with more accumulated luminosity at the HL-LHC. These are typically extremely time-consuming searches, because they require extensive understanding of the background and subtle systematic effects. A long, arduous program of measurements and signal characterization is necessary to investigate these BSM signals. Such signatures could also be produced indirectly via interactions with the electroweak bosons, or the Higgs. In this case, such signatures will have much lower cross sections, and again require rigorous understanding of the SM background.

Overall, the LHC search program has an extensive future in the HL-LHC era and beyond. We should not give up hope only because our preferred ideas do not correspond to what actually exists in the universe.

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