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Beyond Standard Model Theory

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I review the current status of high-energy particle theory beyond the Standard Model. I highlight a few research directions that might provide interesting developments in the near future. These include, in particular, new scenarios related to electroweak naturalness and to the Higgs boson, flavor physics and model-independent approaches for new-physics searches.

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1. Introduction: BSM and the LHC

The discovery of the Higgs boson [1, 2], whose properties at the present level of experimental accuracy perfectly agree with the ones predicted by the Standard Model (SM) [3,4], deeply changed our point of view on high-energy particle physics. Thanks to the Higgs, the SM is a perfectly consistent theory, whose predictions can be extrapolated up to very high energy scales (in principle, even up to the Planck scale).

One immediate consequence of the Higgs discovery is the end of the era of "guaranteed discoveries", since no "no-loose" theorem is available to ensure the presence of new physics in the energy range accessible today or in near future experiments. But on the other hand, many open questions are still there, which require a deeper understanding of the SM itself and, in several cases, imply the presence of new phenomena beyond the SM.

The naturalness problem, i.e. the issue of understanding the origin of the Higgs mass and of the electroweak (EW) scale, has been for decades the main guideline for beyond the SM (BSM) exploration, and is now made real by the Higgs discovery. Although its traditional minimal solutions are nowadays in trouble due to the LHC exclusions, naturalness remains an important issue to be understood, being related to the deep structure of the UV completion of the SM (see section 2).

The crisis of the traditional BSM scenarios, however, stimulated a healthy change of attitude in the particle theory community. On the one hand, the theoretical exploration of BSM solutions to the naturalness problem moved towards alternative paradigms abandoning unmotivated prejudices (as for instance minimality). On the other hand, the experimental searches for BSM signals started to broaden their set of targets, looking for "non-standard" signatures and new strategies for data analysis, or devising new experimental probes "beyond colliders".

It must be stressed that the naturalness problem is not the only reason, perhaps nowadays not even the most compelling one, to search for new physics. In fact, overwhelming experimental evidence is there for phenomena that can not be accommodated within the SM. Striking examples are provided by dark matter, neutrino masses, inflation and baryogenesis. Moreover, several SM aspects seem to point towards a deeper structure at higher energy scales, most noticeably the flavor puzzle, including the strong CP problem. The very precise flavor data, indeed, can offer a powerful complementary way to look for new phenomena, since they are indirectly sensitive to new physics scales well above the EW one.

2. Naturalness and Predictivity

The main issue related to naturalness is the question of whether the value of the Higgs mass and of the EW scale can be *explained* within a UV completion of the SM. This question is related to the particular origin of the Higgs mass in the SM. The Higgs mass term $\mu^2 H^\dagger H$, indeed, is the only super-renormalizable operator in the SM Lagrangian. As such it is the only term associated to a dimensionful parameter, $\mu = m_H/\sqrt{2} \simeq 88$ GeV.

Dimensionful coefficients, in the absence of a symmetry protection, potentially suffer from a naturalness problem. Since μ^2 can be *additively* renormalized (in contrast, for instance, to the Yukawa couplings that are multiplicatively renormalized), it is sensitive to any new physics scale which is coupled to the Higgs boson. If we assume that the explanation of the origin of the Higgs mass is related to new physics at the SM cut-off $\Lambda_{\rm SM}$, quantum corrections would suggest that $\mu^2 \sim \Lambda_{\rm SM}^2$. This relation obviously can not hold if we postpone the appearance of new physics to very high energy scales ($\Lambda_{\rm SM} \gg$ TeV), in which case an unexplained hierarchy is present. This is the essence of the naturalness issue.[1]

It is important to stress that the naturalness problem is not an inconsistency of the SM. In the SM the Higgs mass is just a free parameter that must be fixed through the experiments. The problem only arises if we ask for a microscopic explanation of the value of the Higgs mass. In such case we would like to be able to *predict* the value of the Higgs mass from the input parameters of the fundamental theory. If a large separation between the Higgs mass and the scale of new physics is present, however, predictivity might be lost, as we will argue shortly.

The connection of the naturalness problem with predictivity can be appreciated through a semi-quantitative argument, in terms of the level of fine-tuning needed to obtain the Higgs mass. We can split the full contributions (including radiative corrections) to the Higgs mass into two pieces: one, $\delta_{\rm SM} m_H^2$, coming from the dynamics below the SM cut-off and one, $\delta_{\rm BSM} m_H^2$, from the UV dynamics above $\Lambda_{\rm SM}$. In this way we can write

$$m_H^2 = \delta_{\rm SM} m_H^2 + \delta_{\rm BSM} m_H^2 \,. \tag{2.1}$$

The first contribution can be estimated from the fact that the complete UV theory must reduce to the SM below the cut-off. The largest contributions therefore comes from top loops and is of order

$$\delta_{\rm SM} m_H^2 \simeq \frac{3 y_t^2}{8\pi^2} \Lambda_{\rm SM}^2 \,, \tag{2.2}$$

where $y_t \simeq 1$ is the top Yukawa coupling. The BSM contribution is instead related to the UV completion of the SM and can not be predicted if we do not know such theory. Since we know the Higgs mass from the experiments, we can extract one important implication from eq. (2.1). If $\Lambda_{\rm SM}$ is much above the TeV scale, the SM contribution $\delta_{\rm SM} m_H^2$ is much larger than the measured Higgs mass. In this case the BSM contribution must cancel $\delta_{\rm SM} m_H^2$, with a degree of fine-tuning of order

$$\Delta \sim \frac{\delta_{\rm SM} m_H^2}{m_H^2} \simeq \frac{3 y_t^2}{8\pi^2} \frac{\Lambda_{\rm SM}^2}{m_H^2} \simeq \left(\frac{\Lambda_{\rm SM}}{450\ {\rm GeV}} \right)^2 , \tag{2.3}$$

where we used $m_H \simeq 125$ GeV.

In a "natural" situation we expect $\Delta \lesssim 1$, whereas if $\Delta \gg 1$ we conclude that a significant amount of fine-tuning (or "un-naturalness") is present. In the former case if we are able to measure the fundamental parameters of the UV theory with fair accuracy, we can deduce the value of $\delta_{\rm BSM} m_H^2$, and from this extract a prediction for the Higgs mass. On the contrary if a significant amount of tuning is present, a very detailed cancellation is there between the SM and the BSM contributions in eq. (2.1). In such case, in order to predict the Higgs mass, we would need to know $\delta_{\rm BSM} m_H^2$ with a precision at least of order $1/\Delta$. It is immediately clear that if the cancellation is too strong, we would never be able to measure the UV parameters in such way to match the $1/\Delta$ accuracy. In this situation the Higgs mass can not be predicted anymore from the UV theory. Instead it just remains as a free parameter that can be only fixed through the experiment, but not explained from a fundamental point of view.

Depending on which option is realized in nature, we can identify three main scenarios.

[1] For recent discussions about the naturalness problem see refs. [5, 6].

i) *Full predictivity*. The classical solutions to the naturalness problem advocate the absence of tuning, and therefore full predictivity, by introducing some new dynamics not far from the TeV scale. Through a suitable symmetry structure, the new dynamics stabilizes the Higgs mass, reducing its sensitivity to radiative corrections. Classical examples of such constructions are provided by low-energy supersymmetry and composite Higgs (CH) models.

A remarkable property of these scenarios is the fact that new states are predicted with a mass close to the TeV and thus potentially accessible at the LHC. In particular, in order to regulate the radiative contributions of the top quark to the Higgs mass (see eq. (2.2)), a set of partners of the top must be present. Such partners are typically charged under QCD (as it happens for the stops in supersymmetry and for the fermionic top partners in CH models), so that they have sizable production cross sections at hadron colliders and constitute the main experimental signature of this class of models.

ii) *No predictivity*. At the opposite extreme we have models which completely abandon the predictivity paradigm. The Higgs mass is the result of a large amount of fine-tuning and is thus “un-natural”, therefore it becomes a free parameter, whose value can only be measured experimentally but not explained. Even in this case, however, we need a reason for which the Higgs can be light [5].

The most motivated scenarios in this class feature a huge landscape of vacua (which can be realized, for instance, in string theory models). The huge set of vacua guarantees that some of them have the correct Higgs mass (and the correct cosmological constant, if we also want to address this additional problem). Anthropic reasoning is then advocated to explain why we happen to live in the “correct” vacuum [7, 8].

The cut-off of un-natural models can in principle be much higher than the TeV scale, so that no specific low-energy signatures are expected. This does not mean that no new physics could be there within the range of present experiments. In fact some new dynamics could be accidentally light.

A second class of non-predictive models, dubbed “UV natural” in ref. [5], is based on the assumption that no new-physics threshold contributes to the Higgs mass, which appears as an input parameter as in the SM. One critical aspect of these theories is the fact that an unavoidable threshold necessarily coupled to the Higgs is the quantum gravity scale. There is no obvious reason for which radiative contributions to the Higgs mass involving gravity should vanish. Therefore one would roughly expect $\delta_{\rm BSM} m_H^2 \sim M_{\rm Pl}^2$. There is however the theoretical possibility that the quantum-gravity corrections vanish. This possibility is still open today, since no proof in either direction is available. In these scenarios new physics could exist at the EW or at heavier scales, but its properties are severely constrained by the requirement not to destabilize the Higgs mass [9, 10].

iii) *Semi-predictivity*. Recently, a third scenario that can be thought as intermediate between the previous two emerged. In this class of models, a mini-landscape exists in which a set of minima with the correct size of the Higgs mass is present. However, differently from the classical landscape scenarios based on the anthropic selection, in these theories the EW vacuum satisfies a criticality condition and is determined dynamically through the cosmological evolution of a suitable scalar field. A typical feature of these models is the fact that the overall size of the Higgs mass can be predicted from the UV theory, but not its exact value, since due to quantum effects the exact vacuum selected dynamically can not be predicted.

A class of theories implementing this idea is provided by the "cosmological relaxation" models [11], which we will discuss later on. Although no new physics is generically expected around the EW scale, this scenario features new, typically light, axion-like particles.

We will now discuss a few example of new interesting research directions related to naturalness that have been recently proposed.

2.1 Modifying classical scenarios: Maximally symmetric CH models

As we mentioned, classical solutions of the naturalness problem are nowadays in trouble due to the LHC exclusions. One example is provided by the minimal CH scenarios [12], in which the Higgs arises as a composite state (usually a Goldstone boson) from a new strongly-coupled dynamics around the TeV scale (see ref. [13] for a recent review). The main actors related to the solution of the naturalness problem are a set of fermionic partners of the top, whose mass in minimal models is structurally related to the Higgs potential and to the amount of tuning [14, 15]. In fact they control the generation of the Higgs mass, which can be estimated as

$$\delta m_H^2 \sim \frac{3}{16\pi^2} y_t g_* m_*^2\,, \tag{2.4}$$

where m_* and g_* are the typical mass scale and coupling of the composite states (notice that for a strongly coupled dynamics we expect $g_* \gtrsim few$). The current LHC exclusions [16–18], as well as the bounds from EW precision measurements [19] and Higgs couplings deviations [20], put a lower bound on the top partner masses $m_* \gtrsim 1.3$ GeV. This translates into a *minimal* amount of tuning $1/\Delta \sim few\,\%$, which can be achieved only if the top partners are close to the LHC exclusion.

The strong constraints and the significant amount of tuning in minimal CH models are deeply connected to the minimality assumption. Something similar happens also in minimal supersymmetric theories, such as the MSSM. Non-minimal construction can instead significantly improve the situation allowing for models with heavier new physics that, nevertheless, still have an acceptable amount of fine-tuning.

A nice example of such theory is the recently proposed "Maximally symmetric CH" scenario [21]. In these models the minimal symmetry breaking pattern characterizing the top partners, $\mathrm{SO}(5)_L \times \mathrm{SO}(5)_R \to \mathrm{SO}(4)$, is enlarged to $\mathrm{SO}(5)_L \times \mathrm{SO}(5)_R \to \mathrm{SO}'(5)$, where $\mathrm{SO}'(5)$ is a non-diagonal subgroup of the L and R groups. The extended symmetry has the advantage of significantly reducing the radiative contributions of the top partners to the Higgs mass term (but, in some models, not to the higgs quartic). It therefore allows us to realize models with "minimal tuning", reducing the amount of cancellation in the Higgs mass term with respect to the traditional CH constructions. Maximally symmetric models, with an acceptable amount of tuning (of order *few* %), can push the top partner masses to a scale $m_* \simeq few$ TeV, well above the LHC constraints.

2.2 Elusive New Physics

One of the reasons that put traditional natural scenarios under pressure is the fact that they exploit the presence of partners of the top that are charged under QCD and therefore easily testable at hadron colliders. The fact that top partners are charged under QCD is an obvious expectation, since they must "regulate" the top-loop contributions to the Higgs mass. However, with clever model building, one can engineer scenarios in which the stability of the Higgs potential is ensured by partners that are *neutral* under QCD. This idea, usually dubbed "neutral naturalness", allows for a significant reduction of the production cross section of top partners at hadron colliders, thus making this kind of new physics "elusive".

A simple way to implement neutral naturalness is the "twin Higgs construction" [22]. In these models two copies of the SM degrees of freedom are present, which are related by a Z_2 "mirror" symmetry. The discrete symmetry ensures that radiative corrections to the Higgs potential respect an enhanced symmetry, namely $SU(4)$,

$$V(H,H') \sim -\frac{\Lambda_{\rm SM}^2}{16\pi^2} y_t^2 (|H|^2 + |H'|^2)\,. \tag{2.5}$$

The Higgs is now a pseudo-Goldstone boson coming from $SU(4)$, but the top partners are neutral under the SM gauge symmetry, in particular under our QCD.

In the original construction of ref. [22] an exact mirror copy of the SM is included. This however gives rise to strong constraints from cosmological probes due to the presence of partners of the light-generation fermions. However, alternative models with an approximate mirror symmetry can improve the compatibility with the experimental data (see for instance refs. [23–27]).

2.3 Semi-predictivity: Relaxion

Cosmological relaxation scenarios [11] provide a new mechanism for generating and explaining the observed value of the Higgs mass in terms of the parameters of a fundamental theory. The main idea is a backreaction mechanism, in which the vacuum expectation value (VEV) of a light scalar field ϕ, the "relaxion", controls the Higgs mass. The relaxion VEV undergoes a cosmological evolution until the Higgs acquires a negative mass and breaks the EW symmetry.

The general structure of a potential giving rise to the relaxion mechanism is [28]

$$V(\phi,h) = \Lambda^3 g\,\phi - \frac{1}{2}\Lambda^2\left(1 - \frac{g\,\phi}{\Lambda}\right) h^2 + \varepsilon\,\Lambda_c^4 \left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)\,, \tag{2.6}$$

where n is a positive integer. In the above equation Λ is the cut-off of the model, while g is a small coupling constant characterizing the breaking of the relaxion shift symmetry $\phi \to \phi + c$. The last term in the potential induces an additional breaking of the shift symmetry, whose strength is characterized by the parameter ε, the scale Λ_c. This breaking respects a discrete shift $\phi \to \phi + 2\pi f$.

The first term in the potential provides a tilt that makes the ϕ VEV evolve in time. This evolution reflects into a change in the value of the Higgs mass (second term in the potential), which "scans" a large set of values. When the Higgs mass becomes negative, the Higgs acquires a VEV, breaking the EW symmetry and induces an oscillating contribution to the relaxion potential (last term in eq. (2.6)). When this contribution becomes large enough to provide a suitable barrier, the evolution of ϕ stops, fixing the VEV of the Higgs to a value of order

$$\langle h \rangle \sim g \frac{\Lambda^3 f}{\Lambda_c^3 \varepsilon} \ll \Lambda \qquad \text{for} \quad g \ll 1\,. \tag{2.7}$$

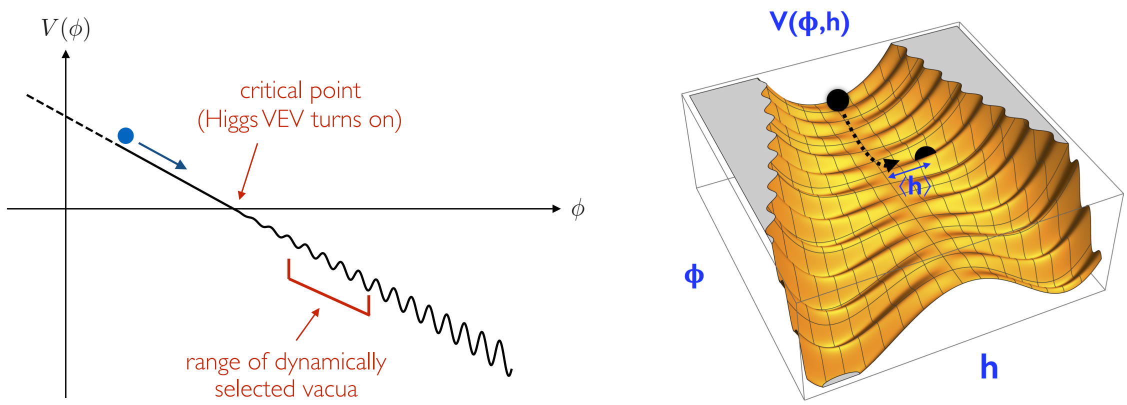

Figure 1: Cartoons showing the evolution of the relaxion field ϕ and of the Higgs field h in the minimal models of cosmological relaxation. The left plot shows the potential for the relaxion field minimizing over the Higgs VEV. On the right the full potential in a region in which $m_h^2 < 0$ is shown.

A schematic cartoon of the potential and of the relaxion evolution is shown in figure 1.

In order not to be forced to fine-tune the initial value of the relaxion VEV, we need to assume that some source of friction is present, which can dissipate the huge amount of energy initially stored in the relaxion field. A possible source of friction is Hubble friction, that is there if the relaxation mechanism takes place during the inflationary epoch. An alternative could be provided by friction through particle production, as proposed in ref. [29].

It is important to stress that, since the evolution of the relaxion field necessarily depends on quantum fluctuations, the minimum in which the relaxion stops can not be fully predicted. One can only predict a range of minima that could be populated. All these vacua have similar values for the Higgs mass and the EW scale, therefore we can derive an estimate for the Higgs mass and for the EW scale in terms of the fundamental parameters of the theory. Nevertheless, we can not predict their exact values. This explains why we dubbed this type of models “semi-predictive”.

The origin of the oscillating term in the relaxion potential can be different depending on the value of n. For $n = 1$ it must be generated by a dynamics that breaks the EW symmetry. In principle we could identify this dynamics with QCD, which can provide an axion potential from the QCD condensate ($\Lambda_c = \Lambda_{\rm QCD}$). This model, however, is ruled out by a too large value of the $\theta_{\rm QCD}$ angle, unless additional structure is introduced at the price of significantly constraining the cut-off ($\Lambda \lesssim 30$ TeV). For $n = 2$, instead, the oscillating term can originate from a new sector that does not break the EW symmetry. Also in the case, however, the scale of this sector can not be much higher than the TeV.

A possible ways to raise the cut-off is to consider extended relaxion models including two scalar fields, in which case a cut-off $\Lambda \sim 10^6$ TeV could be obtained [28]. These constructions can also provide a viable dark matter candidate and a rich phenomenology.

Usually the relaxion field is light and very weakly coupled to the SM states. Therefore its production cross section at colliders is quite small. In this case non-collider searches, including table-top axion experiments or cosmological probes could be used to test these scenarios. For a discussion about the relaxion phenomenology see for instance ref. [30].

3. Beyond Naturalness

As mentioned in the introduction, naturalness is not the only reason to look for BSM physics. Many open questions, whose answer is not provided by the SM are there. Many of them are related to cosmology and astrophysics observations, namely the unknown nature of dark matter, the origin of baryogenesis and the dynamics responsible for inflation. Neutrino masses provide another piece of evidence for BSM dynamics. Moreover the flavor structure of the SM, and in particular the strong CP problem, seem to point out the necessity of a richer structure at higher energy scales.

Differently from the naturalness problem that is obviously related to the EW scale, all the other open questions can not be easily associated to a well-defined energy scale. Known solutions for any of these problems predict new physics that can span many orders of magnitude in energy. Particularly striking is the dark matter case, for which candidates of basically any mass (from 10^{-20} TeV to solar-mass objects) have been proposed.

This however does not mean that new physics connected to these questions is out of reach at present experiments. For instance dark matter or axion searches span a large range of masses, and the extreme precision of flavor measurements can be used to indirectly probe new physics much above the TeV. Furthermore, we need to remember that new physics not necessarily connected to the naturalness problem could happen, for accidental reasons, to be within the reach of collider experiments, in particular the LHC.

I will now focus on a couple of examples of scenarios in which direct collider searches and indirect probes "beyond colliders" provide a complementary way to look for new physics.

3.1 EW baryogenesis and the Higgs sector

An important issue that can not be addressed within the SM is the mechanism responsible for baryogenesis. The Sakharov's conditions for a successful baryogenesis require a departure from thermal equilibrium and a strong enough source of CP violation. Both elements are missing in the SM, which predicts very weak phase transitions (for instance the EW one is just a cross-over) and CP-violating effects strongly suppressed by the flavor structure.

An interesting possibility to realize baryogenesis is to extend the SM Higgs sector in such a way to obtain a strong first order phase transition around the EW scale. Minimal models that implement this idea exploit an extra singlet scalar field [31–37]. In a sizable portion of the parameter space, such models give rise to a two-step EW phase transition: at an intermediate stage only the singlet field η takes a VEV, and only afterwards the EW symmetry is broken through a VEV for the Higgs. A cartoon of the two-step transition is shown in the left panel of figure 2. Interestingly, the second phase transition can be strongly first order if a suitable barrier exists between the two minima, as it happens if the "portal" interaction $\lambda_{h\eta}\eta^2 H^\dagger H$ is sufficiently large.

Renormalizable models with an extra singlet, however, usually lack the required amount of CP violation, which must come from some additional dynamics. An interesting alternative is provided by strongly-coupled versions of this scenario, which can be realized either identifying the additional singlet with a dilaton [39–42] or considering CH models with an extended symmetry [38, 43, 44]. In these cases, thanks to the presence of non-renormalizable couplings of the singlet to the SM fermions (typically to the third-generation quarks), an additional source of CP violation is present during the first-order phase transition.

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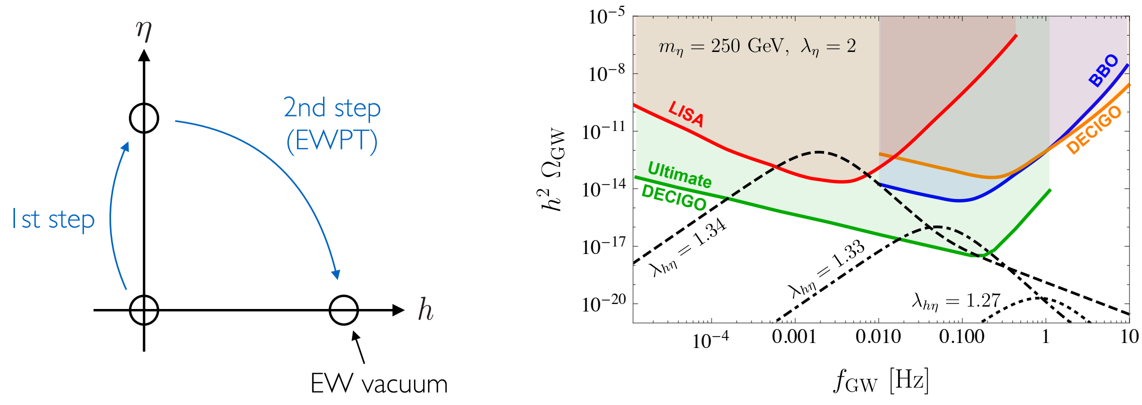

Figure 2: (Left) Schematic cartoon of the two-step EW phase transition in models with an extra scalar singlet. (Right) Example of gravitation wave signal from the first-order EW transition in a CH model with an extra scalar singlet (taken from ref. [38]).

A way to test these scenarios is to exploit direct searches for the singlet at collider experiments. Although the production cross section at the LHC is too low to be tested, future colliders (for instance a 100 TeV pp machine) could cover a significant part of the parameter space [34].

A complementary way to test this scenario is through the observation of gravitation waves (see for instance ref. [45]). The huge release of energy during the first-order EW transition, manifests itself also through the production of gravitational waves, whose peak frequency is within the range of future space-based experiments, such as LISA, BBO end DECIGO. Examples of spectra for a CH model are shown, together with the expected experimental reach, in the right panel of figure 2.

3.2 The flavor frontier: EDMs

Another intriguing aspect of the SM is its flavor structure, whose peculiarities suggest the presence of a deeper dynamics at high energy. Flavor tests are a powerful tool to probe new physics, because the SM flavor sector is characterized by a set of accidental symmetries that strongly suppress flavor-changing and CP-violating effects. These symmetries are quite "fragile" and are typically lost in BSM scenarios due to the presence of additional resonances or additional complex parameters. As a consequence, the flavor data translate into indirect probes for new physics that can test energy scales well above the TeV.

Recently an important experimental development came from the determination of the electron electric dipole moment (EDM), d_e. The ACME II collaboration [46] improved the previous accuracy by almost one order of magnitude, reaching the bound $|d_e| < 1.1 \times 10^{-29}\, e\,\mathrm{cm}$. This level of precision provides not only a good quantitative improvement, but, even more interestingly, a qualitative one [47]. In generic BSM scenarios, the bound before ACME II could be translated into a test of new physics above the TeV scale in the case in which CP-violating effects in EDMs were generated at the one-loop level. Several BSM flavor constructions, however, postpone the appearance of EDM contributions to the two-loop level, thus escaping the experimental bounds (see for instance the CH flavor structure proposed in ref. [48]). The new constraints, on the contrary, are strong enough to test TeV-scale new physics, even if it contributes to the EDMs at the two-loop order.

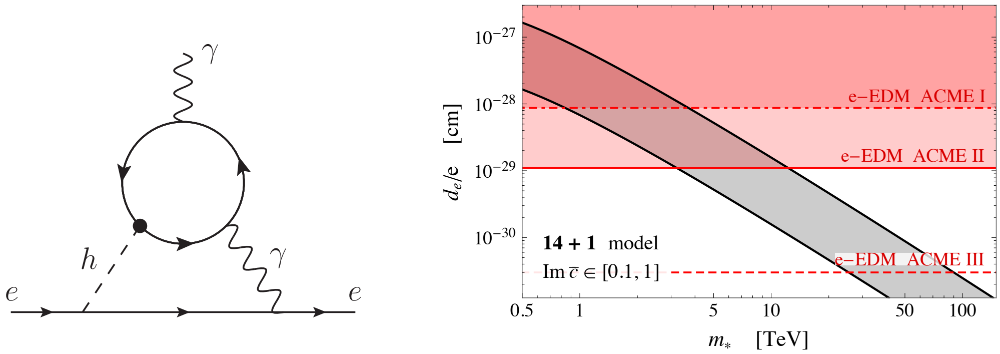

Figure 3: (Left) Example of Barr–Zee-type contribution to the electron EDM. The black dot denotes a CP-violating coupling of the Higgs. (Right) Exclusion on the top partners mass m_* coming from electron EDM bounds. The gray band shows the range of prediction for the EDM contributions as a function of the partner mass. The bounds refer to the $\mathbf{14}+\mathbf{1}$ CH model discussed in ref. [49].

Notice that two-loop EDM effects are nearly unavoidable in BSM extensions of the SM. Universal contributions coming from Barr–Zee-type diagrams [50] (see left panel of figure 3) arise from many types of BSM dynamics, for instance an extended Higgs sector, fermionic top partners or supersymmetric states. As can be seen from the right panel in figure 3, the current bounds can easily test new physics in the $5-10$ TeV range (in the plot the exclusions for top partners in a CH model are shown). These bounds are therefore competitive with, and in many cases stronger than, the direct search constraints from the LHC.

It must also be stressed that EDM bounds can also play an important role in constraining EW baryogenesis models, since these scenarios unavoidably need additional sources of CP violation to satisfy Sakharov's conditions.

4. Model-independent approaches

The third, and last, topic I discuss is the model-independent approach to new-physics searches at colliders. The aim of these attempts is to look for new physics in a virtually *unbiased* way, relying almost exclusively on the SM predictions, with a minimal set of additional assumptions about the BSM dynamics. One can immediately understand that this approach has the advantage of looking for a wide spectrum of new-physics models within a "unified" framework. Moreover it can potentially be sensitive to classes of new physics that have not yet been explored theoretically.

Present research lines focus on two main model-independent approaches, namely precision measurements and, more recently, anomaly detection.

4.1 Precision measurements

The precision measurement approach exploits the fact that a new-physics dynamics, even if too heavy to be directly accessed, still induces corrections to the SM predictions for low-energy observables. If one is able to measure with enough precision the SM processes, one can thus look for these small traces. In the previous section we already saw that this approach can be quite fruitful in the case of flavor observables, for which extreme precisions can be achieved experimentally. A similar strategy, as I will now discuss, can be used for EW and Higgs observables at colliders.

The main framework to parametrize deviations from the SM is provided by the effective-field-theory (EFT) approach. If new physics is heavy enough not to be directly produced, we can "integrate it out" parametrizing its effects on low-energy observables through a set of higher-dimensional operators added to the renormalizable SM Lagrangian. These operators are usually arranged in a series in the dimension of the operators

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathscr{O}_i^{dim-6} + \sum_i \frac{d_i}{\Lambda^4}\mathscr{O}_i^{dim-8} + \cdots . \tag{4.1}$$

At low energy, operators with lower dimension are expected to produce the largest contributions, so that one usually truncate the expansion at the level of dimension-6 operators.

The EW precision measurement program was carried out successfully at LEP, which provided an excellent precision for EW observables thanks to the low systematic errors. For instance the oblique parameters [51, 52], which parametrize deviations in the propagators of the EW gauge boson, were measured with a precision of order 10^{-3} corresponding to new-physics scales of the order of a few TeV.

A similar program can be carried out at hadron colliders, and in particular at the LHC, in spite of the much more complicated environment due to QCD effects. The key observation is the fact that deviations in SM observables induced by non-renormalizable operators tend to *grow* with the energy of the process. For instance, for dimension-6 operators we expect $\Delta\mathscr{O}/\mathscr{O} \sim E^2/\Lambda^2$. This observation makes clear the fact that being able to access higher energies allows for an enhancement of the BSM effects making them visible even if the overall experimental accuracy is at the *few %* level. For this to be viable one therefore needs to look for channels in which the enhancement is there and in which the theory and experimental errors can be kept under control [53].

The simplest example is provided by di-lepton Drell–Yan production, which can be used to test the W and Y oblique parameters, corresponding to the operators

$$-\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 - \frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2 . \tag{4.2}$$

In this process a precision of order $3-5$ % can be achieved at the LHC up to center-of-mass energies of order $2-3$ TeV. The 8 TeV LHC data are already enough to match the LEP bounds, $|W|,|Y| \lesssim 10^{-3}$ [53]. The 13 (or 14) TeV high-luminosity runs will be able to improve these bounds by roughly one order of magnitude. It can be shown that these constraints can nicely complement direct searches, extending the experimental sensitivity to regions of the parameter space with heavy resonances or signals difficult to be disentangled from the backgrounds. The W parameter, for example, can be used to put bounds on the mass of massive vectors and is competitive with direct searches in the small coupling region [53].

Many other channels can be exploited for EW precision measurements at the LHC. Most noticeably the di-boson production processes (involving a pair of gauge bosons or the Higgs). These channels can be useful to probe a broader class of BSM scenarios and to test the strength of the Higgs interactions at high energy [54–61].

4.2 Anomaly detection

Anomaly detection is an alternative model-independent approach to the search for new physics that tries to detect deviations from a given reference model (the SM) with no need to specify an alternative theory. One can immediately understand that this approach has the advantage to be ideally sensitive to any new-physics model. The price to pay, is the fact that this method can not be used to derive exclusions on specific BSM scenarios. In fact this approach is informative only if a positive signal is found, but does not tell us anything about new physics (not even exclusions) if the data agree with the SM.

The main anomaly detection strategies are heavily based on machine learning techniques. The main idea behind those is to use the experimental data and a reference sample from the SM to infer the compatibility between the two. In this way a test statistics can be obtained which can then be used for the usual statistical analysis.

Anomaly detection applications in collider physics are still at an early-development stage. Many directions are currently under investigation, among which

- CWoLa hunting [62],
- Novelty detection [63],
- Distribution comparison [64–66],
- Non-QCD jets [67, 68],
- Gaussian mixture pdf [69],
- Nearest-neighbours pdf [70].

5. Conclusions

In spite of the lack of unambiguous new-physics signs at present experiments, the exploration of BSM scenarios is still in strong active development, with many new research directions opened in recent years.

The search for natural implementations of the EW symmetry breaking dynamics, which is deeply related to the issue of predictivity of the UV completion of the SM, is moving towards alternative scenarios; either considering non-minimal constructions and “elusive” solutions, or proposing completely new paradigms, such as the cosmological relaxation ideas.

At the same time, several open SM issues show the need to carry out of a BSM search program as broad as possible. One important direction is given by collider search strategies that encompass a larger set of new-physics signatures, possibly in a model-independent way. Other options are related to beyond-collider experiments, which can provide a useful, complementary way to enlarge the class of testable new-physics scenarios.

To conclude these proceedings I would like to answer a question, which is a key point in years in which our perspective on particle physics is deeply changing: *is theory still important?* I strongly believe that the answer is affirmative. As argued in the previous sections, naturalness is still an important issue that can tell us something about the UV completion of the SM. Moreover theory plays a crucial role in planning existing and new experiments, and interpreting the data. Theoretical models are, indeed, a useful tool to explore new-physics signatures and to provide adequate frameworks for the experimental searches. Finally, as we discussed in section 4, even model-independent search strategies need a strong theory input to be fully effective.

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References

[1] G. Aad *et al.* [ATLAS Collaboration], *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. B **716** (2012) 1 [arXiv:1207.7214 [hep-ex]].

[2] S. Chatrchyan *et al.* [CMS Collaboration], *Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC*, Phys. Lett. B **716** (2012) 30 [arXiv:1207.7235 [hep-ex]].

[3] G. Aad *et al.* [ATLAS Collaboration], *Combined measurements of Higgs boson production and decay using up to* 80 fb^{-1} *of proton-proton collision data at* $\sqrt{s} = 13$ *TeV collected with the ATLAS experiment*, arXiv:1909.02845 [hep-ex].

[4] A. M. Sirunyan *et al.* [CMS Collaboration], *Measurement and interpretation of differential cross sections for Higgs boson production at* $\sqrt{s} = 13$ *TeV*, Phys. Lett. B **792** (2019) 369 [arXiv:1812.06504 [hep-ex]].

[5] G. F. Giudice, *Naturalness after LHC8*, **PoS EPS-HEP2013** (2013) 163 [arXiv:1307.7879 [hep-ph]].

[6] R. Barbieri, *Electroweak theory after the first Large Hadron Collider phase*, Phys. Scripta T **158** (2013) 014006 [arXiv:1309.3473 [hep-ph]].

[7] S. Weinberg, *Anthropic Bound on the Cosmological Constant*, Phys. Rev. Lett. **59** (1987) 2607.

[8] V. Agrawal, S. M. Barr, J. F. Donoghue and D. Seckel, *Viable range of the mass scale of the standard model*, Phys. Rev. D **57** (1998) 5480 [arXiv:hep-ph/9707380].

[9] M. Shaposhnikov, *Is there a new physics between electroweak and Planck scales?*, arXiv:0708.3550 [hep-th].

[10] M. Farina, D. Pappadopulo and A. Strumia, *A modified naturalness principle and its experimental tests*, JHEP **1308** (2013) 022 [arXiv:1303.7244 [hep-ph]].

[11] P. W. Graham, D. E. Kaplan and S. Rajendran, *Cosmological Relaxation of the Electroweak Scale*, Phys. Rev. Lett. **115** (2015) no.22, 221801 [arXiv:1504.07551 [hep-ph]].

[12] K. Agashe, R. Contino and A. Pomarol, *The Minimal composite Higgs model*, Nucl.Phys. **B719** (2005) 165 [arXiv:hep-ph/0412089].

[13] G. Panico and A. Wulzer, *The Composite Nambu-Goldstone Higgs*, Lect. Notes Phys. **913** (2016) pp. 1-316 [arXiv:1506.01961 [hep-ph]].

[14] O. Matsedonskyi, G. Panico and A. Wulzer, *Light Top Partners for a Light Composite Higgs*, JHEP **1301** (2013) 164 [arXiv:1204.6333 [hep-ph]].

[15] G. Panico, M. Redi, A. Tesi and A. Wulzer, *On the Tuning and the Mass of the Composite Higgs*, JHEP **1303** (2013) 051 [arXiv:1210.7114 [hep-ph]].

[16] O. Matsedonskyi, G. Panico and A. Wulzer, *Top Partners Searches and Composite Higgs Models*, JHEP **1604** (2016) 003 [arXiv:1512.04356 [hep-ph]].

[17] CMS collaboration, *Search for top quark partners with charge 5/3 in the same-sign dilepton and single-lepton final states in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*, JHEP **03** (2019) 082 [arXiv:1810.03188 [hep-ex]].

[18] ATLAS collaboration, *Search for diboson resonances in hadronic final states in 139* fb^{-1} *of pp collisions at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, arXiv:1906.08589 [hep-ex].

[19] C. Grojean, O. Matsedonskyi and G. Panico, *Light top partners and precision physics*, JHEP **1310** (2013) 160 [arXiv:1306.4655 [hep-ph]].

[20] ATLAS collaboration, *Constraints on new phenomena via Higgs boson couplings and invisible decays with the ATLAS detector*, JHEP **1511** (2015) 206 [arXiv:1509.00672 [hep-ex]].

[21] C. Csaki, T. Ma and J. Shu, *Maximally Symmetric Composite Higgs Models*, Phys. Rev. Lett. **119** (2017) no.13, 131803 [arXiv:1702.00405 [hep-ph]].

[22] Z. Chacko, H. S. Goh and R. Harnik, *The Twin Higgs: Natural electroweak breaking from mirror symmetry*, Phys. Rev. Lett. **96** (2006) 231802 [arXiv:hep-ph/0506256].

[23] N. Craig, S. Knapen and P. Longhi, *Neutral Naturalness from Orbifold Higgs Models*, Phys. Rev. Lett. **114** (2015) no.6, 061803 [arXiv:1410.6808 [hep-ph]].

[24] M. Geller and O. Telem, *Holographic Twin Higgs Model*, Phys. Rev. Lett. **114** (2015) 191801 [arXiv:1411.2974 [hep-ph]].

[25] N. Craig, A. Katz, M. Strassler and R. Sundrum, *Naturalness in the Dark at the LHC*, JHEP **1507** (2015) 105 [arXiv:1501.05310 [hep-ph]].

[26] R. Barbieri, D. Greco, R. Rattazzi and A. Wulzer, *The Composite Twin Higgs scenario*, JHEP **1508** (2015) 161 [arXiv:1501.07803 [hep-ph]].

[27] M. Low, A. Tesi and L. T. Wang, *Twin Higgs mechanism and a composite Higgs boson*, Phys. Rev. D **91** (2015) 095012 [arXiv:1501.07890 [hep-ph]].

[28] J. R. Espinosa, C. Grojean, G. Panico, A. Pomarol, O. Pujolàs and G. Servant, *Cosmological Higgs-Axion Interplay for a Naturally Small Electroweak Scale*, Phys. Rev. Lett. **115** (2015) no.25, 251803 [arXiv:1506.09217 [hep-ph]].

[29] A. Hook and G. Marques-Tavares, *Relaxation from particle production*, JHEP **1612** (2016) 101 [arXiv:1607.01786 [hep-ph]].

[30] T. Flacke, C. Frugiuele, E. Fuchs, R. S. Gupta and G. Perez, *Phenomenology of relaxion-Higgs mixing*, JHEP **1706** (2017) 050 [arXiv:1610.02025 [hep-ph]].

[31] J. R. Espinosa, T. Konstandin and F. Riva, *Strong Electroweak Phase Transitions in the Standard Model with a Singlet*, Nucl. Phys. B **854** (2012) 592 [arXiv:1107.5441 [hep-ph]].

[32] J. M. Cline and K. Kainulainen, *Electroweak baryogenesis and dark matter from a singlet Higgs*, JCAP **1301** (2013) 012 [arXiv:1210.4196 [hep-ph]].

[33] S. Profumo, M. J. Ramsey-Musolf, C. L. Wainwright and P. Winslow, *Singlet-catalyzed electroweak phase transitions and precision Higgs boson studies*, Phys. Rev. D **91** (2015) no.3, 035018 [arXiv:1407.5342 [hep-ph]].

[34] D. Curtin, P. Meade and C.-T. Yu, *Testing Electroweak Baryogenesis with Future Colliders*, JHEP **1411** (2014) 127 [arXiv:1409.0005 [hep-ph]].

[35] M. Kakizaki, S. Kanemura and T. Matsui, *Gravitational waves as a probe of extended scalar sectors with the first order electroweak phase transition*, Phys. Rev. D **92** (2015) no.11, 115007 [arXiv:1509.08394 [hep-ph]].

[36] V. Vaskonen, *Electroweak baryogenesis and gravitational waves from a real scalar singlet*, Phys. Rev. D **95** (2017) no.12, 123515 [arXiv:1611.02073 [hep-ph]].

[37] G. Kurup and M. Perelstein, *Dynamics of Electroweak Phase Transition In Singlet-Scalar Extension of the Standard Model*, Phys. Rev. D **96** (2017) no.1, 015036 [arXiv:1704.03381 [hep-ph]].

PoS(EPS-HEP2019)707

[38] S. De Curtis, L. Delle Rose and G. Panico, *Composite Dynamics in the Early Universe*, arXiv:1909.07894 [hep-ph].

[39] T. Konstandin and G. Servant, *Cosmological Consequences of Nearly Conformal Dynamics at the TeV scale*, JCAP **1112** (2011) 009 [arXiv:1104.4791 [hep-ph]].

[40] S. Bruggisser, B. Von Harling, O. Matsedonskyi and G. Servant, *Baryon Asymmetry from a Composite Higgs Boson*, Phys. Rev. Lett. **121** (2018) no.13, 131801 [arXiv:1803.08546 [hep-ph]].

[41] S. Bruggisser, B. Von Harling, O. Matsedonskyi and G. Servant, *Electroweak Phase Transition and Baryogenesis in Composite Higgs Models*, JHEP **1812** (2018) 099 [arXiv:1804.07314 [hep-ph]].

[42] P. Baratella, A. Pomarol and F. Rompineve, *The Supercooled Universe*, JHEP **1903** (2019) 100 [arXiv:1812.06996 [hep-ph]].

[43] B. Gripaios, A. Pomarol, F. Riva and J. Serra, *Beyond the Minimal Composite Higgs Model*, JHEP **0904** (2009) 070 [arXiv:0902.1483 [hep-ph]].

[44] M. Frigerio, A. Pomarol, F. Riva and A. Urbano, *Composite Scalar Dark Matter*, JHEP **1207** (2012) 015 [arXiv:1204.2808 [hep-ph]].

[45] J. Ellis, M. Lewicki and J. M. No, *On the Maximal Strength of a First-Order Electroweak Phase Transition and its Gravitational Wave Signal*, JCAP **1904** (2019) 003 [arXiv:1809.08242 [hep-ph]].

[46] V. Andreev *et al.* [ACME Collaboration], *Improved limit on the electric dipole moment of the electron*, Nature **562** (2018) no.7727, 355.

[47] G. Panico, A. Pomarol and M. Riembau, *EFT approach to the electron Electric Dipole Moment at the two-loop level*, JHEP **1904** (2019) 090 [arXiv:1810.09413 [hep-ph]].

[48] G. Panico and A. Pomarol, *Flavor hierarchies from dynamical scales*, JHEP **1607** (2016) 097 [arXiv:1603.06609 [hep-ph]].

[49] G. Panico, M. Riembau and T. Vantalon, *Probing light top partners with CP violation*, JHEP **1806** (2018) 056 [arXiv:1712.06337 [hep-ph]].

[50] S. M. Barr and A. Zee, *Electric Dipole Moment of the Electron and of the Neutron*, Phys. Rev. Lett. **65** (1990) 21 Erratum: [Phys. Rev. Lett. **65** (1990) 2920].

[51] M. E. Peskin and T. Takeuchi, *Estimation of oblique electroweak corrections*, Phys. Rev. D **46** (1992) 381.

[52] R. Barbieri, A. Pomarol, R. Rattazzi and A. Strumia, *Electroweak symmetry breaking after LEP-1 and LEP-2*, Nucl. Phys. B **703** (2004) 127 [hep-ph/0405040].

[53] M. Farina, G. Panico, D. Pappadopulo, J. T. Ruderman, R. Torre and A. Wulzer, *Energy helps accuracy: electroweak precision tests at hadron colliders*, Phys. Lett. B **772** (2017) 210 [arXiv:1609.08157 [hep-ph]].

[54] A. Azatov, J. Elias-Miro, Y. Reyimuaji and E. Venturini, *Novel measurements of anomalous triple gauge couplings for the LHC*, JHEP **1710** (2017) 027 [arXiv:1707.08060 [hep-ph]].

[55] G. Panico, F. Riva and A. Wulzer, *Diboson Interference Resurrection*, Phys. Lett. B **776** (2018) 473 [arXiv:1708.07823 [hep-ph]].

[56] R. Franceschini, G. Panico, A. Pomarol, F. Riva and A. Wulzer, *Electroweak Precision Tests in High-Energy Diboson Processes*, JHEP **1802** (2018) 111 [arXiv:1712.01310 [hep-ph]].

[57] D. Liu and L. T. Wang, *Prospects for precision measurement of diboson processes in the semileptonic decay channel in future LHC runs*, Phys. Rev. D **99** (2019) no.5, 055001 [arXiv:1804.08688 [hep-ph]].

[58] S. Banerjee, C. Englert, R. S. Gupta and M. Spannowsky, *Probing Electroweak Precision Physics via boosted Higgs-strahlung at the LHC*, Phys. Rev. D **98** (2018) no.9, 095012 [arXiv:1807.01796 [hep-ph]].

[59] C. Grojean, M. Montull and M. Riembau, *Diboson at the LHC vs LEP*, JHEP **1903** (2019) 020 [arXiv:1810.05149 [hep-ph]].

[60] A. Azatov, D. Barducci and E. Venturini, *Precision diboson measurements at hadron colliders*, JHEP **1904** (2019) 075 [arXiv:1901.04821 [hep-ph]].

[61] F. F. Freitas, C. K. Khosa and V. Sanz, *Exploring the standard model EFT in VH production with machine learning*, Phys. Rev. D **100** (2019) no.3, 035040 [arXiv:1902.05803 [hep-ph]].

[62] J. H. Collins, K. Howe and B. Nachman, *Anomaly Detection for Resonant New Physics with Machine Learning*, Phys. Rev. Lett. **121** (2018) no.24, 241803 [arXiv:1805.02664 [hep-ph]].

[63] J. Hajer, Y. Y. Li, T. Liu and H. Wang, *Novelty Detection Meets Collider Physics*, arXiv:1807.10261 [hep-ph].

[64] J. Brehmer, K. Cranmer, G. Louppe and J. Pavez, *Constraining Effective Field Theories with Machine Learning*, Phys. Rev. Lett. **121** (2018) no.11, 111801 [arXiv:1805.00013 [hep-ph]].

[65] J. Brehmer, K. Cranmer, G. Louppe and J. Pavez, *A Guide to Constraining Effective Field Theories with Machine Learning*, Phys. Rev. D **98** (2018) no.5, 052004 [arXiv:1805.00020 [hep-ph]].

[66] R. T. D'Agnolo and A. Wulzer, *Learning New Physics from a Machine*, Phys. Rev. D **99** (2019) no.1, 015014 [arXiv:1806.02350 [hep-ph]].

[67] J. A. Aguilar-Saavedra, J. H. Collins and R. K. Mishra, *A generic anti-QCD jet tagger*, JHEP **1711** (2017) 163 [arXiv:1709.01087 [hep-ph]].

[68] T. Heimel, G. Kasieczka, T. Plehn and J. M. Thompson, *QCD or What?*, SciPost Phys. **6** (2019) no.3, 030 [arXiv:1808.08979 [hep-ph]].

[69] M. Kuusela, T. Vatanen, E. Malmi, T. Raiko, T. Aaltonen and Y. Nagai, *Semi-Supervised Anomaly Detection - Towards Model-Independent Searches of New Physics*, J. Phys. Conf. Ser. **368** (2012) 012032 [arXiv:1112.3329 [physics.data-an]].

[70] A. De Simone and T. Jacques, *Guiding New Physics Searches with Unsupervised Learning*, Eur. Phys. J. C **79** (2019) no.4, 289 [arXiv:1807.06038 [hep-ph]].

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