PROCEEDINGS OF SCIENCE

Learning from run-2

Andrea Wulzer*
Dipartimento di Fisica e Astronomia "G. Galilei", Università di Padova and INFN, Sezione di Padova, Via Marzolo 8, I-35131 Padova, Italy
E-mail: andrea.wulzer@pd.infn.it

The LHC collider recently started operating at an increased center of mass energy of 13 TeV and will soon collect, during the so-called "run-2", an integrated luminosity of 100 fb^{-1}. In this talk I briefly summarised some of the major physics opportunities offered by run-2 data for the exploration of Beyond the Standard Model physics. These include searches for new phenomena in the Higgs and ElectroWeak sector, resonances and Dark Matter searches.

VII Workshop italiano sulla fisica pp a LHC
16-18 Maggio 2016
Pisa, Italy

*Speaker.

1. Disclaimer

The discovery of the Higgs boson [1, 2] and the measurement of its properties [3, 4] provided the first direct evidence of the validity of the Standard Model (SM) theory of ElectroWeak (EW) and Strong interactions. While not unexpected in view of the strong indirect indications from EW Precision Tests, this discovery has been, together with the lack of discovery of any Beyond the SM (BSM) particle or phenomenon, a revolutionary event for high energy physics. The point is that the SM is a renormalizable theory, and it is the first time in history we happen to have in our hands an experimentally verified renormalizable theory of EW and Strong interactions. The lack of renormalizability of previous theories (see [5] for a pedagogical discussion) made them intrinsically incomplete and not suited to describe Nature at arbitrarily high energy scales. Concrete technical inconsistency emerge in those theories and oblige them to fail at reasonably small energies, within the conceivable reach of colliders. This allowed us to be sure of the existence of New Physics and stimulated the construction of higher and higher energy machines to search for it, with the absolute guarantee of achieving a discovering if overcoming a given energy threshold. Moreover these concrete inconsistencies, associated with the lack of renormalizability, offered a valid guidance for theorists in their efforts towards the formulation of more fundamental theories. All together, this made progresses in high energy physics follow a path of "guided" discoveries in the past few decades. Examples of guided discoveries are the one of the W boson, of the top quark and of course of the Higgs boson. These discoveries were all strongly guided by theory, in the sense that theory was capable to provide very precise indications on the nature and on the specific properties of the new particles well before their actual discovery. The paradigmatic example is the one of the Higgs boson. Assuming the validity of the SM, which was the hypothesis we aimed to test, all Higgs cross-sections and branching ratios were known as a function of a unique unknown parameter: the Higgs boson mass. Furthermore the latter parameter was already constrained by LEP in the relatively narrow range from 115 to 190 GeV.

Such a strong theoretical guidance deeply shaped our attitude towards the search for new phenomena. It is thus important to stress that we are not anymore in this situation. Being the SM renormalizable, there is no concrete obstruction to its validity up to very high energy scales, far above what we could ever directly or indirectly test at colliders in the foreseeable future. The only scale at which new physics is guaranteed to emerge is the Planck scale, precisely because the SM lacks a renormalizable theory of Gravity, but this is by far too high to be ever relevant experimentally. Furthermore the status of BSM physics is that we do have valid and relevant questions to be asked to the data, guided for instance by Naturalness considerations or by the need of explaining the origin of Dark Matter, but no reasons to select one or few specific BSM models as particularly compelling. On one hand, this means that there is nothing as predictive as the Higgs models to be searched for. Rather than BSM "models" we should get used to search for broad BSM "scenarios", exploring their possible experimental manifestations in a generic and model-independent way to the largest possible extent. On the other hand, it means that theoretical BSM considerations might not be the right guidance towards new physics discoveries. Some effort should thus also be devoted to theory-unbiased searches, in final states that appear promising because of their simplicity, of their low background and/or of their purity, irregardless of their BSM motivation. Being a theorist, I will however only discuss theory-motivated searches in what follows.

PoS(PP@LHC2016)001

2. Higgs Couplings and Beyond

A lot of efforts were made in the last few years to establish the properties of the Higgs boson and to measure its couplings using the 8 (and 7) TeV LHC data collected at run-1. These measurements produced constraints on several BSM scenarios and in particular on those, such as Composite Higgs [6] and Supersymmetry, that solve the Higgs mass Naturalness problem. Addressing Naturalness (in the "canonical" sense at least) indeed generically requires modifying the SM in the Higgs sector and, more generally, in the whole EW sector. The specific way in which these modifications emerge depends however on the specific BSM scenario. Composite Higgs and Supersymmetry behave for instance slightly differently as discussed below.

The impact of Higgs couplings measurements on Composite Higgs models is well illustrated by Fig. 1, which shows the ATLAS [3] and CMS [4] fit results in the κ_V–κ_F plane. Following the standard notation, κ_V represents the deviation with respect to the SM prediction of the Higgs couplings to massive vector bosons, while κ_F is a universal modification of fermion couplings. The Composite Higgs predictions are also shown in the plot as curves parametrised by $\xi \in [0,1]$, where

$$\xi = \frac{v^2}{f^2} \,. \tag{2.1}$$

In the equation, f is the so-called "decay constant" of the composite Higgs boson while $v \simeq$ 246 GeV is the EWSB scale. The role played by f in Composite Higgs models is the one of a new physics scale, therefore it is expected (though non-trivial) that all the BSM effects should disappear when $f \to \infty$ (i.e., $\xi \to 0$) and the new physics decouples. The Composite Higgs formulae for κ_V and κ_F read

$$\kappa_V = \sqrt{1-\xi}\,, \quad \kappa_F^{\mathbf{4}} = \sqrt{1-\xi}\,, \quad \kappa_F^{\mathbf{5}} = \frac{1-2\xi}{\sqrt{1-\xi}}\,, \tag{2.2}$$

and indeed they approach the SM, $\kappa_V = \kappa_F = 1$, for $\xi = 0$. Notice also that the prediction for κ_F is not unique. A discrete ambiguity emerges from the need of choosing, when building models, the representation of the symmetry group in which certain operators, related with the generation of fermion Yukawa couplings, are assumed to live. The case of a **4** and of a **5** of SO(5), corresponding to the so-called Minimal Composite Higgs Models ($\mathrm{MCHM}_{4,5}$) are reported in Eq. (2.2) and displayed in Fig. 1.[1] In Ref. [8], the ATLAS collaboration performed a dedicated statistical analysis to set upper limits on ξ using Higgs couplings measurements, obtaining $\xi < 0.12$ in the MCHM_4 and $\xi < 0.10$ in the MCHM_5 at 95% CL.

There are two aspects of this result which is worth outlining. The first one is the theoretical relevance of the bound on ξ, due to the connection of the ξ parameter with the amount of fine-tuning Δ which is needed to reproduce the correct EWSB scale. The inverse of ξ sets, up to order

[1] Other options exist and might be also considered, though not big changes are expected in the final result. The study might also be generalised to non-Minimal Composite Higgs models where, unlike the Minimal setup assumed in Fig. 1, extra scalars are present on top of the ordinary Higgs doublet. The extra scalars could affect the Higgs coupling modification predictions by mixing with the ordinary Higgs and of course also be relevant for direct searches.

PoS(PP@LHC2016)001

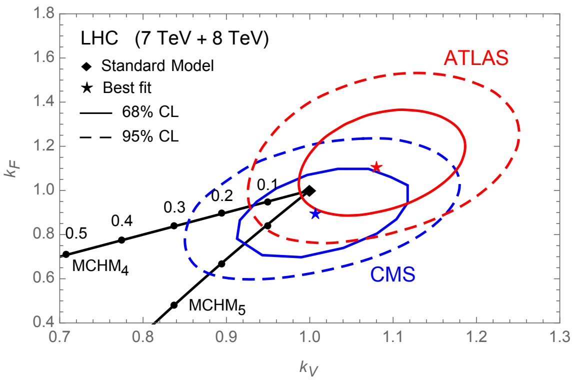

Figure 1: Fit of the Higgs coupling strength to the gauge bosons (k_V) and fermions (k_F) obtained by the ATLAS (red contours) and CMS collaborations (blue contours) from the combination of the 7 and 8 TeV LHC data. The solid black lines show the predictions in the $\mathrm{MCHM}_{5,4}$ models for different values of ξ.

one numerical factors, a lower bound on Δ, namely [2]

$$\Delta \gtrsim \frac{1}{\xi} . \tag{2.3}$$

Run-1 limits on $\xi \lesssim 0.1$ thus push Composite Higgs models towards the 1-digit level of Un-Natural cancellation. The second important aspect of the run-1 limit on ξ is that it is slightly stronger than the one we would have expected to obtain in the SM hypothesis. It is driven, as Fig. 1 clearly shows, by the fact that the ATLAS central value sits above the SM prediction, especially in the κ_V direction, while $\kappa_V < 1$ in Composite Higgs models. As a result of this, the current limit on ξ is already as strong as the one expected at the end of run-2, or even at the end of the LHC program with 300 fb^{-1} [9, 10, 11]. This makes progresses very difficult and the discovery of a non-vanishing ξ virtually impossible to occur at run-2.

The situation is similar for Supersymmetric solutions to the Naturalness problem, though there are also relevant differences to be outlined. Like in Composite Higgs, the Higgs sector in Supersymmetry is different from the SM one, involving at least two Higgs doublets as in the Minimal Supersymmetric Standard Model (MSSM). The second doublet mixes with the first one producing modified Higgs couplings to up- and down-type fermions and vectors

$$\kappa_u = \frac{\cos\alpha}{\sin\beta} \simeq 1 - \frac{1}{1+t_\beta^2}\varepsilon\,, \quad \kappa_d = -\frac{\sin\alpha}{\cos\beta} \simeq 1 + \frac{t_\beta^2}{1+t_\beta^2}\varepsilon\,, \quad \kappa_V = \sin(\beta-\alpha) \simeq 1 - \mathscr{O}(\varepsilon^2)\,,$$
$$\tan\alpha = \frac{(m_A^2+m_Z^2)t_\beta}{m_h^2(1+t_\beta^2) - m_Z^2 - m_A^2 t_\beta^2} \simeq -\frac{1}{t_\beta} + \mathscr{O}(\varepsilon)\,, \tag{2.4}$$

where $t_\beta = \tan\beta$ is the ratio between up- and down-type Higgs VEVs, m_A is the mass of the CP-odd extra Higgs scalar and $m_h = 125$ GeV. The expansion for $\varepsilon = m_h^2/m_A^2 \ll 1$ is also reported in

[2]The relation that follows might have been guessed from the definition of ξ in Eq. (2.1), which involves the ratio between the low-energy SM scale v and the one of new physics f. However its validity cannot be proven in full generality, but only parametrically established in all known "plain" realisations of the Composite Higgs scenario. In line of principle, Composite Higgs scenarios might exist in which ξ is Naturally small and Eq. (2.3) is violated. Known examples involve extra ingredients and their viability still needs to be assessed.

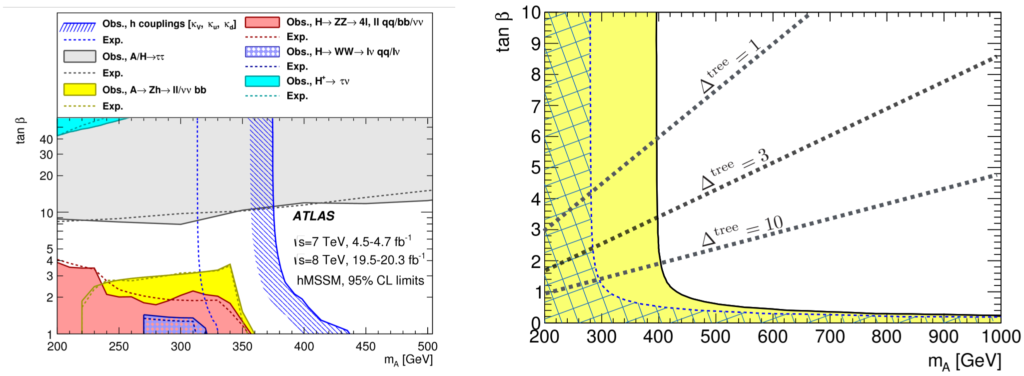

Figure 2: Left panel: the constraints on the MSSM from Higgs physics as reported in Ref. [8]. Right panel: bounds from Higgs coupling measurements (from a plot in a preliminary version of Ref. [8]) on which I overlaid the "tree-level" tuning contours.

the equation. This formula allows us to set limits from the Higgs coupling measurements in the $(m_A, \tan\beta)$ plane, on which the bounds from direct searches of extra scalars can also be reported. The result, obtained by ATLAS in Ref. [8], is shown in the left panel of Fig. 2. The limit from Higgs couplings measurements observed by ATLAS is slightly stronger than the expected one. Like in the Composite Higgs case we are thus led to negative expectations towards run-2 improvements.

What is different in the MSSM with respect to Composite Higgs models is the actual relevance of Higgs sector bounds, as quantified in terms of fine-tuning. Unlike in Composite Higgs, the MSSM Higgs sector is not directly related with the level of fine-tuning which is present in the theory because of the existence of the so-called "decoupling limit". In the limit, $m_A \to \infty$, so that all the extra scalars become too heavy to be produced, the couplings (2.4) approach their SM values and all the bounds disappear. The limit is taken by simultaneously sending $t_\beta \to \infty$, along a direction which is technically Natural, in the following sense. Obtaining the correct EWSB scale from the minimisation of the potential requires imposing on the parameters of the theory a certain condition, which for $t_\beta \gg 1$ reads [3]

$$\frac{m_Z^2}{2} \simeq \frac{m_A^2}{t_\beta^2} - \widetilde{m}_u^2\,, \quad \text{where} \quad \widetilde{m}_u^2 = \mu^2 + m_u^2 + \delta\,. \tag{2.5}$$

As m_A increases, the first term in the Z mass formula becomes larger and larger and a more and more accurate cancellation has to be enforced with the second term in order to reproduce m_Z. If however t_β also increases, such as to keep m_A/t_β fixed at the EW scale, the first term remains small and no fine-tuning is required. More technically, the level of tuning can be estimated as

$$\Delta^{\rm tree} = \frac{(m_A/t_\beta)^2}{(m_Z/\sqrt{2})^2} \simeq \left(\frac{6}{t_\beta}\right)^2 \left(\frac{m_A}{400\,\text{GeV}}\right)^2\,. \tag{2.6}$$

Contour lines of $\Delta^{\rm tree}$ in the $(m_A, \tan\beta)$ plane, displayed on the right panel of Fig. 2, show the lack of a correlation between the boundary of the region we can constrain and the level of fine-tuning. This makes scalar sector physics arguably less interesting in the MSSM than in Composite Higgs.

[3] In the equation that follows, μ is the SUSY mass, m_u is the soft up-type mass and δ accounts for the radiative contribution to the Higgs quartic in the notation of Ref. [8].

PoS(PP@LHC2016)001

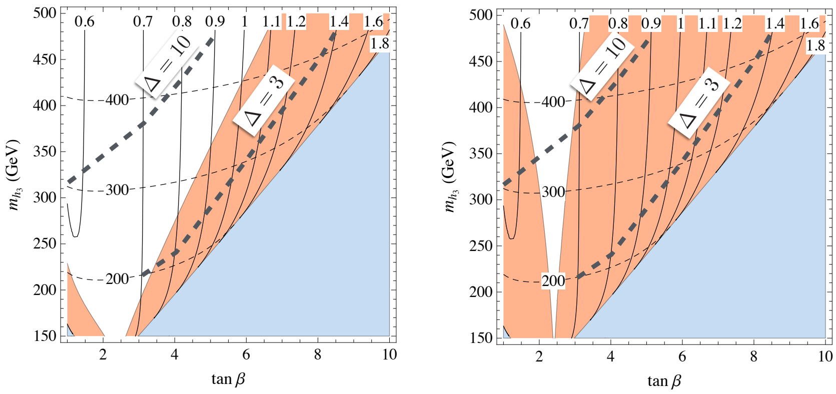

Figure 3: Bounds [15] on λSUSY from Higgs coupling measurements in the plane $(\tan\beta, m_{h_3})$ where $m_{h_3} = m_H$ is the mass of the CP-even Higgs. The orange regions are excluded by the measurements while the blue ones are not theoretically accessible. The plots refers to the limiting situation where the additional CP-even scalar from the extra singlet is decoupled. The left panel shows current limits from the 7 and 8 TeV results of the LHC, the right panel is a projection of the 13 TeV reach.

However the MSSM, as we now know for sure after the direct measurement of $m_h \simeq 125$ GeV, is not the appropriate model to discuss Naturalness in the SUSY context. A much larger source of fine-tuning exists than the "tree-level" one we accounted for by Eq. (2.6). The well-known problem is that m_h is smaller than m_Z at tree-level and making it large enough requires a sizeable radiative correction to the Higgs quartic term in the potential. This correction grows logarithmically with the mass of the stops and is unavoidably accompanied by a correction to the up-type mass-term m_u^2 that instead grows like the stop mass squared. This needs to be canceled not to produce an unacceptably large second term in Eq. (2.5), resulting in a large fine-tuning. The estimate of Ref. [12] is that stops as heavy as at least 1 TeV are needed and the tuning is $\Delta > 100$. Therefore the MSSM is not a Natural theory and furthermore we have little chances to discover it at the LHC given that the entire SUSY spectrum could be above the TeV.[4]

The considerations above strongly motivate the study of alternative SUSY models, among which the λSUSY framework [14] emerges as a particularly plausible option. In λSUSY, an extra singlet chiral super-multiplet S is added to the MSSM and coupled through a term $\lambda S H_u H_d$ in the superpotential. This gives a new contribution to the Higgs quartic term that can produce, if $\lambda \gtrsim 1$, a large enough Higgs mass already at the tree-level, with no need of heavy stops and large fine-tuning from radiative corrections. To be precise, and this is very important for the considerations that follow, the mechanism requires not only sizeable λ, but also moderate t_β below around 10. Therefore the Natural decoupling limit of the MSSM, with large t_β, cannot be taken in λSUSY and a more direct connection is present between Naturalness and Higgs physics. This is shown in Fig. 3 (see Ref. [5] for details), where the constraints from Higgs coupling measurements are superimposed with equal-tuning contour lines. Run-1 data (left panel) exclude tuning at the level of a few, while 300 fb^{-1} at the 13 TeV LHC (right panel) will probe $\Delta \sim 10$. Unlike in Composite

[4]For a fair comparison with the composite Higgs scenario, I should mention that the 125 GeV Higgs discovery also had an impact on composite Higgs constructions, though not as dramatic as on the MSSM. Namely, the relatively light Higgs mass obliges certain particles, the "Top Partners", to be light and within the LHC reach [13]. This is another important implication of Higgs physics on BSM.

PoS(PP@LHC2016)001

Higgs, a slight improvement of the limits should be possible at run-2 within the λSUSY framework, mainly driven by the more accurate determination of the Higgs coupling to τ's. In view of these considerations, and because of the relevance of λSUSY for Naturalness, I believe that this is an important subject that deserves further attention and dedicated experimental studies at run-2.

Beyond Higgs Couplings

Refining Higgs couplings measurements is definitely an important goal of the LHC run-2. However the previous discussion clearly shows that progresses are difficult, or even impossible in some cases, because the expected run-2 limits are not far from those we already set at run-1. To some extent this is due to the upper fluctuation of the ATLAS limit, but also and more importantly to the fact that the accuracy in the measurements will not improve much at run-2 with respect to run-1. For instance, the expected reach on ξ in Composite Higgs (which is a good measure of the couplings determination accuracy) was around 0.2 at run-1, is around 0.1 with 300 fb^{-1} at 13 TeV and will almost not improve further with the 3000 fb^{-1} of the foreseen High-Luminosity (HL) stage of the LHC [9, 10, 11]. This suggests that Higgs couplings measurements are about to reach the irreducible threshold due to systematics and encourages us to look for alternative strategies to test indirect manifestations of BSM physics.

Two elements are relevant for the discussion. The first is that modifications of the on-shell Higgs couplings are necessarily part of a larger set of new physics effects which involve the whole EW sector and affect a variety of EW processes. If new physics is heavy, these effects are conveniently and model-independently described by $d=6$ operators to be added to the SM Lagrangian.[5] The second element is that these new physics effects might be more conveniently seen in high-energy scattering processes, not necessarily involving the Higgs as a final state, rather than by studying Higgs production, which occurs at relatively low energy. This is because corrections to the SM from $d=6$ operators grow with the energy, $\Delta\sigma/\sigma \propto E^2$, and get amplified at high energy. We can appreciate the power of this enhancement by considering the oblique parameters W and Y studied at LEP [18] and comparing the LEP reach with the one obtainable at the LHC. At LEP, limits on W and Y were set by very precise measurements, at the per mille level, of neutral-current EW processes at a center of mass energy of around 100 GeV. But W and Y correspond to the coefficients of two $d=6$ operators and their effect on the cross-section grows quadratically with the energy, growing by a factor of 100 for 1 TeV reactions, which the LHC is capable to produce. The LHC reach would thus be comparable with the one of LEP even with a 10% accuracy measurement of the high-energy cross-section. A slightly better accuracy is actually obtainable, leading to the rather surprising conclusion that the LHC could perform better than LEP on the determination of some of the oblique parameters.

While some examples of this behaviour are present in the literature, a comprehensive assessment of the reach on new physics from the measurement of high-energy cross-sections is still missing. Several groups of phenomenologists are however active in this direction and rapid progresses are expected. From the experimental side, several high-energy differential cross-section measurements are being (and even more should be) performed. Relevant channels are first of all dilepton, $l\nu$ and diboson (including the Higgs) production, but also final states involving the top

[5] See for instance [16, 17] for a lucid discussion.

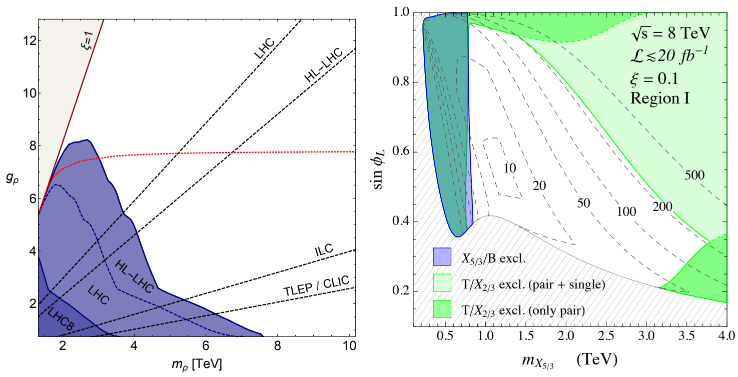

Figure 4: Left plot: current and expected limits on HVT's, from Ref. [20]. Middle and right: bounds from Top Partners searches on a simplified Composite Higgs model [21]. Contour lines of the level of fine-tuning which is present in the model are showed in dashed.

quark should be considered. Unlike Higgs couplings, those measurement will greatly improve with the new experimental conditions available at run-2. Indeed, parton luminosities above 1 TeV increase at 13 TeV by one order of magnitude with respect to 8 TeV, giving access to higher energy regions where new physics effects are enhanced. Also, run-2 will benefit of an higher luminosity (which will be further extended in the next run and at the HL-LHC) which reduces statistical errors. Measuring high-energy differential cross-section is a promising direction where to look for new physics at run-2, to be further explored.

3. Resonances

It is obvious, and very well known, that run-2 will greatly improve the reach of heavy resonance searches thanks to the higher collider energy. I will briefly illustrate this point by means of two examples, merely selected as those I'm most familiar with, which are relevant for the Composite Higgs scenario. The first example is the one of the Heavy Vector Triplets (HVT), which are spin-one resonances produced in Drell-Yan and decaying in dilepton or in diboson final states [19, 20]. Run-1 limits on these particles, the final reach of the LHC with 300 fb^{-1} and the one of HL-LHC are displayed in the left panel of Fig. 4. On top of the mass m_ρ, the limit depends on the couplings strength parameter g_ρ, which in Composite Higgs can be large, easily around 3 or more. The figure gives an idea of how much the reach will improve, both in the high-mass and in the large-g_ρ (i.e., small production rate) directions. Indirect limits from Higgs coupling constraints on ξ, obtained by the rough estimate $\xi \simeq g_\rho^2 v^2/m_\rho^2$ as explained in [20], are also reported for comparison.

The second example, displayed in the middle and right panel of Fig. 4, is the one of fermionic Top Partners [21]. These particles are vector-like coloured heavy fermions strongly coupled with the top and the bottom quarks, which are efficiently produced in pairs by QCD interactions but also singly, in association with third family quarks and a forward energetic light jet. The impact of current and future Top Partners exclusions is quantified in a particularly simple Composite Higgs model, in the plane defined by the mass of one of the partners (the one of electric charge $5/3$) and the compositeness fraction of the left-handed top quark. While by far not representative of the

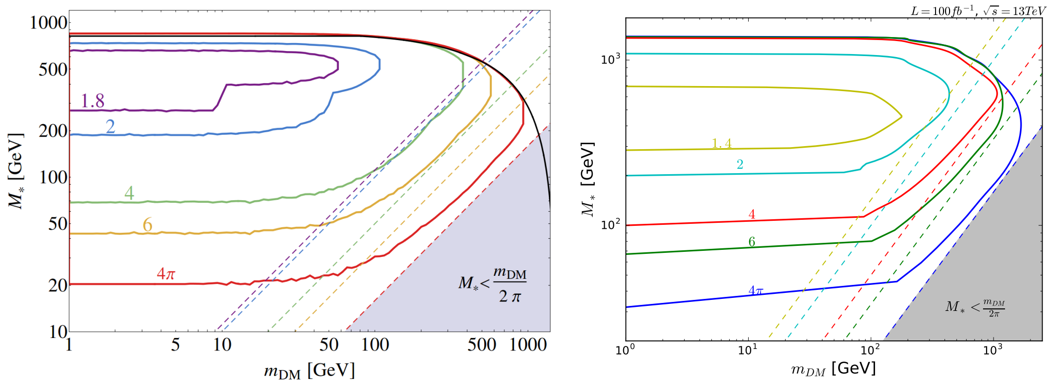

Figure 5: EFT limits on DM at run-1 and run-2 projections [22, 23]. Run-1 limits are obtained from the recast of an ATLAS analysis in the mono-jet channel.

Composite Higgs scenario in full generality (other models are also considered in [21]), limits in this simple model are sufficient to give an idea of the impact of Top Partner searches. The result is that run-1 limits leave open a considerable fraction of the parameter space, which run-2 could easily close with only 20 fb^{-1} of integrated luminosity. The plots are for $\xi = 0.1$, right at the boundary of the region excluded by Higgs coupling measurements. Smaller values, around $\xi = 0.05$, will be probed with the full run-2 luminosity of 100 fb^{-1}.

4. Dark Matter

Assessing the current status and the future perspectives of Dark Matter (DM) searches at the LHC is a difficult task, in which I will not succeed. Indeed, it is unclear what we should take as a sensible "figure of merit" to quantify the performances of DM searches. Clearly the problem has to do with the fact that the properties of DM are largely unknown, so that it is very difficult to formulate reasonably generic benchmark models which would allow us to translate the experimental results into reasonably model-independent limits on DM. The (proper [22]) usage of Effective Field Theories (EFT) offers a partial way out to this situation. The advantage of EFT's is that they provide a concise model-independent description of DM production, in terms of one (or few) $d = 6$ effective operator coefficient $1/M_*^2$, which is universally valid if the DM interaction with the SM particles is mediated by the exchange of heavy particles, much above the DM mass m_{DM}. The disadvantage is that the EFT is a partial description of the DM production processes. Namely it is valid, in the sense that it reproduces what one would obtain in any explicit DM model with heavy mediators, only for reactions taking place below the typical mass of the mediator sector particles. From the viewpoint of the EFT, this scale corresponds to and additional parameter called the EFT cutoff $M_{\rm cut}$. Only processes occurring below $M_{\rm cut}$ must be considered to set a consistent limit on DM within EFT's [22]. However detecting DM production requires a considerable amount of transverse activity (in the form of MET and of a visible object such as a jet or a photon), which in turn requires processes as hard as few hundreds of GeV's. At low $M_{\rm cut}$, the restricted EFT signal is too soft to be detected and the search looses sensitivity.

Run-1 limits on DM EFT's and a preliminary run-2 projection [23] are shown in Fig. 5 in the m_{DM}-M_* plane. The third parameter, $M_{\rm cut}$, has been traded for a coupling strength parameter $g_* = M_{\rm cut}/M_*$. Fixing g_* produces closed exclusion regions as displayed in the figure. The limit deteriorates and eventually disappears at small g_*, i.e. at small $M_{\rm cut}$, as previously explained. Notice that g_* is a coupling strength, which can be interpreted as the typical coupling strength of the mediator sector particles. For a "WIMP", couplings of the order of the weak one are expected and it is thus rather worrisome that $g_* = g_W \sim 1$ is outside the run-1 reach. Moreover, we see that no much progress is expected at run-2, but this is somehow unavoidable because the production rate scales like $1/M_*^4$ within the EFT. The modest improvement of the reach on M_* and the consequent modest improvement on g_* actually corresponds to a considerable improvement on the excluded partonic cross-section.

While useful and definitely worth presenting, the EFT interpretation of DM searches is not the universally valid figure of merit we were seeking for. The negative conclusion we reached above on the run-2 perspectives should thus be taken with great care. The point is that the EFT limits become weak in a region (of low $M_{\rm cut}$ and small g_*) which might on the contrary be favourable for detection from the viewpoint of the underlying theory. This is indeed precisely the region where the mediator sector is light and most likely it consists of a set of weakly coupled narrow particles, which could be efficiently produced on-shell as narrow resonances. In this region, DM searches effectively turn into resonance searches for the mediator particles and as such they should be interpreted. Obviously, this requires making some hypothesis on the nature and the dynamics of the mediators. However I seriously doubt that fully specifying one or few (conventionally chosen) benchmark models, as recommended by the LHC DM Working Group [24], is really the only way to proceed. While definitely useful to compare the performances of different experiments, this approach prevents the interpretation of the limits in real DM models and thus it is not the optimal way to transmit the information about the LHC findings on DM to future generations. On the contrary, one should try to report the limits on the mediators in a model-independent format, relying on the minimal possible set of assumptions on their properties. In the true spirit of Simplified Models [25], [6] one option could be to report limit on on-shell production cross-sections and branching ratios, depending on whether the mediator has an s- or a t-channel coupling to DM and, if needed, on its spin.

5. Diphoton

At the time this talk was given, some excesses observed by ATLAS and CMS in run-1 and early run-2 diphoton searches were statistically and theoretically (i.e., in view of other bounds) compatible with the existence of a 750 GeV mass resonance. More data collected in 2016 have now shown that those excesses were (rare) statistical fluctuations of the SM background. However thinking about the diphoton excess has been instructive. On one hand, the very fact that a discovery could have been possible, compatibly with all existing bounds, shows how little we know about the TeV scale and confirms that the LHC is exploring virgin territories of fundamental physics. On the other hand, entertaining for few month the concrete possibility that a new particle was about to be discovered made us fully appreciate how revolutionary such a discovery would be and how much

[6] DM Working Group benchmark models are also called "Simplified Models", in spite of the fact that they serve to the opposite purpose than the one advocated in [25].

it would advance our knowledge. Those are both very good reasons to continue searching for new physics at the LHC to the best of our ability.

6. Conclusions

I briefly summarised some of the opportunities offered by run-2 for the study of BSM physics. I discussed the program of Higgs couplings measurement, its extension to a comprehensive study of the EW sector, resonances and DM searches. One should however not forget the Disclaimer of Section 1, namely the fact that BSM theory might not be the right guidance towards the discovery of new physics. Experimental exploration, as opposite to the search for experimental confirmations of theoretical hypotheses, is nowadays more important than ever.

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], arXiv:1507.04548 [hep-ex].

[4] V. Khachatryan *et al.* [CMS Collaboration], Eur. Phys. J. C **75** (2015) 5, 212 [arXiv:1412.8662 [hep-ex]].

[5] A. Wulzer, PoS EPS **-HEP2015** (2015) 005 [arXiv:1510.05159 [hep-ph]].

[6] For a pedagogical introduction and a comprehensive review, see G. Panico and A. Wulzer, Lect. Notes Phys. **913** (2016) pp.1 doi:10.1007/978-3-319-22617-0 [arXiv:1506.01961 [hep-ph]].

[7] A. Pomarol and F. Riva, JHEP **1401** (2014) 151 doi:10.1007/JHEP01(2014)151 [arXiv:1308.2803 [hep-ph]].

[8] G. Aad *et al.* [ATLAS Collaboration], arXiv:1509.00672 [hep-ex].

[9] **CMS** Collaboration, "CMS at the High-Energy Frontier. Contribution to the Update of the European Strategy for Particle Physics", [CMS-NOTE-2012-006].

[10] **ATLAS** Collaboration, "Projections for measurements of Higgs boson cross sections, branching ratios and coupling parameters with the ATLAS detector at a HL-LHC", [ATL-PHYS-PUB-2013-014].

[11] S. Dawson, A. Gritsan, H. Logan, J. Qian, C. Tully *et al.*, "Working Group Report: Higgs Boson", `arXiv:1310.8361` [Inspire].

[12] L. J. Hall, D. Pinner and J. T. Ruderman, JHEP **1204** (2012) 131 [arXiv:1112.2703 [hep-ph]].

[13] O. Matsedonskyi, G. Panico and A. Wulzer, JHEP **1301** (2013) 164 [arXiv:1204.6333 [hep-ph]].

[14] R. Barbieri, L. J. Hall and V. S. Rychkov, Phys. Rev. D **74** (2006) 015007 [hep-ph/0603188].

[15] R. Barbieri, D. Buttazzo, K. Kannike, F. Sala and A. Tesi, Phys. Rev. D **88** (2013) 055011 [arXiv:1307.4937 [hep-ph]].

[16] J. Elias-Miro, J. R. Espinosa, E. Masso and A. Pomarol, JHEP **1311** (2013) 066 doi:10.1007/JHEP11(2013)066 [arXiv:1308.1879 [hep-ph]].

PoS(PP@LHC2016)001

[17] A. Pomarol and F. Riva, JHEP **1401** (2014) 151 doi:10.1007/JHEP01(2014)151 [arXiv:1308.2803 [hep-ph]].

[18] R. Barbieri, A. Pomarol, R. Rattazzi and A. Strumia, Nucl. Phys. B **703** (2004) 127 doi:10.1016/j.nuclphysb.2004.10.014 [hep-ph/0405040].

[19] D. Pappadopulo, A. Thamm, R. Torre and A. Wulzer, JHEP **1409** (2014) 060 doi:10.1007/JHEP09(2014)060 [arXiv:1402.4431 [hep-ph]].

[20] A. Thamm, R. Torre and A. Wulzer, JHEP **1507** (2015) 100 [arXiv:1502.01701 [hep-ph]].

[21] O. Matsedonskyi, G. Panico and A. Wulzer, JHEP **1604** (2016) 003 doi:10.1007/JHEP04(2016)003 [arXiv:1512.04356 [hep-ph]].

[22] D. Racco, A. Wulzer and F. Zwirner, JHEP **1505** (2015) 009 doi:10.1007/JHEP05(2015)009 [arXiv:1502.04701 [hep-ph]].

[23] F. Pobbe, Master Thesis in Padova.

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

[25] N. Arkani-Hamed, P. Schuster, N. Toro, J. Thaler, L. T. Wang, B. Knuteson and S. Mrenna, hep-ph/0703088 [HEP-PH].

PoS(PP@LHC2016)001