APPROACHING A NEW ENERGY FRONTIER AT THE LHC

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Abstract

After reviewing the latest great achievements in the field of Collider Physics, we sketch the main criticalities of the present theory of particle interactions. The latter substantiate the expectations for possible new discoveries at the forthcoming Run II at the Large Hadron Collider (LHC). We discuss the LHC potential in mass reach for the production of new heavy states, and we argue that any kind of clear discrepancy from the Standard Model predictions which will be observed will imply a revolution in the field.

1 Collider Physics: where we stand today

The Large Hadron Collider (LHC), the CERN proton-proton collider with c.m. collision energies of up to 14 TeV, has yet to enter its full running regime, and still has already produced a wealth of most remarkable results. In the

LHC Run 1, spanning the years 2009-2013, the ATLAS and CMS experiments collected each a data set of about 5 fb^{-1} of integrated luminosity at $\sqrt{s} = 7$ TeV plus about 20 fb^{-1} at $\sqrt{s} = 8$ TeV[1]. This was just the initial phase of the machine, which is now expected to collect about 100 fb^{-1} at $\sqrt{s} = 13-14$ TeV in the Run 2 during the years 2015-2018. In the subsequent Run 3, by the year 2023 the LHC should reach a data set of 300 fb^{-1} at the same $\sqrt{s}$, possibly followed by a High-Luminosity phase aiming at collecting about 3000 fb^{-1} at $\sqrt{s} = 14$ TeV in the following 10 years [1)].

Although Run 1 was just the initial LHC phase, both the machine and the experiments had an amazing performance, obtaining results very much above expectations. The standard model (SM) theory has been tested at high accuracy in a new $\sqrt{s}$ range. QCD has been probed in many different regimes, and knowledge of the proton parton distribution functions (PDF's) has been widely extended. Many new results on top quark physics, flavor physics, and electroweak (EW) processes have been collected [2)].

Most importantly, the direct exploration of the SM EW symmetry breaking (EWSB) sector has started up with the observation of a (quite light) Higgs-boson resonance at 125 GeV. The Higgs observation (which was the last missing object among the states predicted by the SM to be experimentally observed) was a triumph for both the SM theory [3)] and the LHC enterprise [4)]. Although the particle observed looks quite similar to the boson predicted in the SM, there is presently still a lot of room for a non-SM EWSB/Higgs sector.

Apart from SM studies, at the Run1, a lot of searches for new heavy states predicted by many beyond-SM (BSM) models have been performed, and the corresponding mass bounds have been widely extended with respect to the pre-LHC era. There are just a few very mild hints at the moment possibly pointing to non-SM phenomena in proton collisions (see e.g. the ATLAS analysis [5)]). Altogether, one can say that the SM theory provides an excellent description of all phenomena studied up to now in high-energy collisions.

The LHC Run-2 just started with stable beams in June 2015, with ATLAS and CMS having already collected about 200 pb^{-1} today [1)], and great expectations for fore-coming results.

[1]Here we are not covering physics studies at the LHCb and ALICE experiments.

2 The Higgs boson sector: criticalities and opportunities

The actual identity of the newly observed particle with mass 125 GeV can be established by measuring with high precision the magnitude and structure of its couplings to known particles. The SM predicts the intensity of the Hpp Higgs coupling is set by the mass of the coupled p particle. Once, the Higgs mass is known, the SM also predicts the scalar boson self-coupling magnitude. From the ATLAS and CMS analysis of the Run 1 data set, one can infer that the observed particle is not a *generic* scalar state, because it really matches the nontrivial coupling pattern predicted in the SM well within errors. The brand new combined ATLAS and CMS results for the measurement of the couplings [6] agrees within 1σ with the SM Higgs-coupling predictions. The measurement of the scalar resonance mass in the $\gamma\gamma$ and 4ℓ channels by the two experiments agrees very well, and provides the result $m_H = 125.09 \pm 0.24$ GeV [7], with the amazing precision of 0.2%.

The test of the SM Lagrangian looks then about to be completed by the direct measurements of all the parameters involved in its Higgs-sector part. Actually, it should be stressed that the main *theoretical shortcomings* of the SM Lagrangian are connected to just its Higgs sector, notably the Yukawa-coupling mysterious hierarchy (which spans many many orders of magnitudes), the fact that the Higgs mass term is not protected by any symmetry, and finally the Higgs self-coupling magnitude which affects the vacuum stability, and the possibility of explaining the Baryogenesis via cosmological EW phase transition.

The unprotected Higgs mass term in the SM Lagrangian motivates the expectation for a New Physics energy threshold as low as o(1) TeV in order to avoid fine-tuning in the fundamental parameters of the theory. Such a low threshold could well give rise to detectable effects at the LHC. After LHC Run 1 searches, the simplest versions of many proposed models able to cure the SM fine-tuning (or *naturalness*) problem look quite fine-tuned. Run 2 will widely expand the coverage of BSM searches, as discussed in the following. It is anyhow important to stress that a general prediction of *natural* models (like the MSSM or the minimal Composite Higgs models), apart from the existence of new heavy states with o(1) TeV masses, is a deviation in the Higgs-boson couplings at the few percents level. The deviation pattern depends on the particular extension of the SM Lagrangian. A very accurate measurement of the

Higgs boson couplings could then detect the inadequacy of the SM even before the direct observation of the predicted heavy states, and point to a particular kind of SM extension. One Higgs coupling which is in general most sensitive to *natural* modifications of the SM Lagrangian is the Higgs self-coupling. Its corresponding measurement, which is unfortunately quite challenging at the LHC, as well as the measurement of all Higgs couplings, will be extremely helpful in characterizing possible SM extensions at the TeV scale, even if they do not manifest in direct production of new states.

3 LHC Run 2 versus LHC Run 1

LHC Run 2 is at the moment characterized by a 13 TeV c.m. collision energy, that could soon be updated to the nominal value of 14 TeV foreseen by the LHC design. This corresponds to a 62% (75% at 14 TeV) increase in the c.m. energy available for the production of new heavy states, with a total integrated luminosity expected to be about 100 fb^{-1} at the end of Run 2 by 2018.

The exploration of a yet unexplored energy domain has just started with a huge discovery potential! Indeed, the mass reach M_{reach} (defined as the heaviest mass of a BSM state that can be directly produced and observed either singly or in pairs) will be drastically extended in Run 2 with respect to the 8-TeV Run. Although the exact mass-reach increase from Run 1 to Run 2 is in general model dependent, it is interesting to approximatly estimate the M_{reach} variation just from the scaling of parton luminosities and PDF's, with the assumption that cross sections scale with the inverse squared system mass [8]. In general, given the higher c.m. energy and related integrated luminosity, starting from the Run-1 8-TeV mass reach M_{reach}^{R1} and event number N_{ev} (corresponding to the 20 fb^{-1} collected data set) for a given signal process, in order to estimate the LHC increase in mass reach at larger $\sqrt{s}$, one can just require the number of events corresponding to Run-2 to be the same N_{ev}, neglecting scaling differences in backgrounds, reconstruction, and detector behavior [8]. For quite large masses (not too close to the edges of available kinematical range), one then finds simple approximate rules governing M_{reach} versus $\sqrt{s}$ and integrated luminosity $\int L$. For instance, one finds that, by increasing $\sqrt{s}$ by a factor x, in order to also extend M_{reach} by a factor x, one needs to increase the integrated luminosity by x^2, which compensates the $1/M^2$ cross section dependence. On the other hand, at fixed $\sqrt{s}$, M_{reach} depends almost logarithmically on $\int L$. For

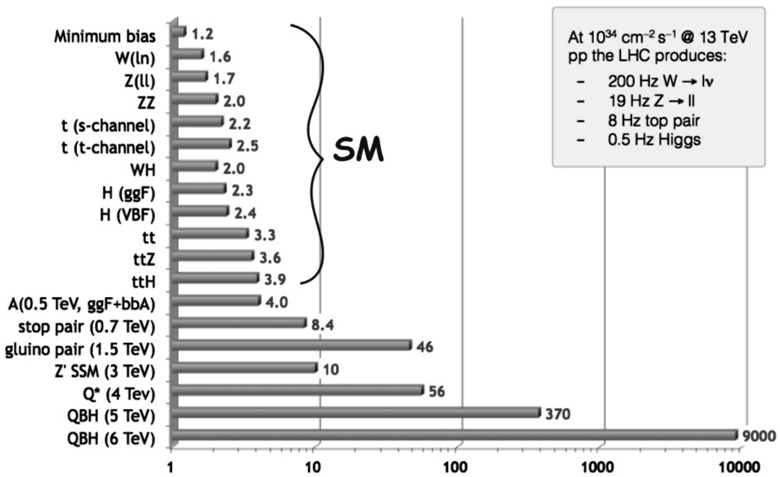

Figure 1: *Cross-section enhancement x factors for different production processes when going from LHC collisions at $\sqrt{s} = 8$ GeV to LHC collisions at $\sqrt{s} = 13$ GeV. The 13-TeV potential approximately equals the Run-1 8-TeV one, after collecting (20/x) fb^{-1} at 13 TeV.*

instance, for $0.15 < \ M_{reach}/\sqrt{s} < \ 0.6$, increasing $\int L$ by a factor 10, M_{reach} grows up to about $M_{reach} + 0.07\sqrt{s}$, which for $\sqrt{s} = 14$ TeV corresponds to a 1-TeV rise. This is relevant for example when going from the LHC projected luminosity of $\int L$ 300 fb^{-1} to the High-Luminosity expected data set of about $\int L$ 3000 fb^{-1}.

In Figure 1, we report the enhancement factor x for cross sections at $\sqrt{s} = 13$ TeV with respect to the 8 TeV cross sections for different production processes. These factors fold the *partonic* cross-section and *partonic* luminosity scaling. At 13 TeV, the Run 1 potential in searches will be approximately matched after collecting just about $(20/x)$ fb^{-1}, which, for particularly heavy states such as gluino pairs in Supersymmetry, requires less than 1 pb^{-1}.

4 Summary and Outlook

The SM has proven to be beautifully successful in any possible test involving c.m. energies covered up to today in collider experiments. Nevertheless, the SM theory many limitations lead us to believe that this framework is not a complete one. In particular, the Higgs boson is the first *possibly* elementary scalar observed in nature, and its theoretical features present a number of criticalities. As a consequence, the precise measurement of the Higgs properties will be, in the forthcoming LHC program, one of the most promising way to "indirectly" discover New Physics and to discriminate among BSM extensions. The search of exotic signatures in Higgs decays and of further heavier Higgs degrees of freedom will also provide a valuable handle for extending our knowledge of the actual (possibly non-standard) Higgs sector.

Indeed, the Higgs-boson observation opened up an entire new chapter of BSM exploration. Even in case of no observation of new heavy states in the next LHC runs, precision Higgs physics will have a key role in paving the way for extending the SM theory.

In any case, LHC Run 2 just started with a great potential for discoveries. There are many different possibilities ahead of us. We might observe new resonances and/or *robust* modifications of distributions or physical observables. This would surely imply a revolution in our understanding of particle interactions. It would also require a huge amount of work in the following years to set the actual SM extension that could accomodate the observed new phenomena. Another option ahead is that we will not observe at the LHC any significant deviation from the SM predictions, and will just keep measuring observables with more and more precision. This latter option would anyway imply a deepening of our knowledge of fundamental interactions at shorter distances, that will have to be taken into account by any possible SM extension.

After the Run-1 completion and the observation of all SM degrees of freedom, however "revolutionary" the forthcoming LHC outcome at 14 TeV will be, it will lay just the first stage of a new path of exploration, which will in no way be a conclusive one for Particle Physics.

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