QCD AND HIGH-ENERGY HADRONIC INTERACTIONS: THEORETICAL SUMMARY

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1 Introduction

The 2013 edition of Moriond QCD offered a complete and exciting overview of the latest progress in a broad variety of topics in elementary particle physics. While the highlight of the meeting was the release of the latest data from the LHC, particularly the update on Higgs studies, excellent contributions on both theoretical and experimental recent results gave a clear sense of vitality, progress, and expectation for further exciting developments to come. The experimental search for and the theoretical speculations about possible phenomena beyond the Standard Model (BSM), remain the driving theme of most studies, but great efforts are fortunately still dedicated to the pursuit of precision, and to a deeper understanding of dynamical issues.

I will loosely group the various contributions in five areas: low-Q^2 dynamics of strong interactions, heavy ion (HI) collisions, precision physics in hadronic collisions, status of BSM and flavour physics and status of electroweak (EW) symmetry breaking (EWSB). The experimental contributions have been reviewed in the excellent Summary talk by Dmitri Denisov [1]. Rather than a summary of the theory talks, I will present a theoretical perspective on the whole set of results, including reference to several experimental talks, to underline issues of theoretical relevance: there is no doubt that the multitude of results made available by the experiments, their precision and diversity, remain the key drivers of today's theoretical progress, and the interplay between theory and experiment represents the most valuable asset of our scientific community.

The following summary shows an unavoidable unbalance between different topics, reflecting the bias due to my personal expertise, understanding, and taste. For the sake of space, I shall refer to the proceedings for a complete bibliography relative to the individual contributions.

2 Low-Q^2 dynamics

After many decades since the acceptance of QCD as the fundamental theory of hadronic interactions, the study of its behaviour in the domain of strong coupling remains as vital as ever. This is confirmed by the diversity of the theoretical and experimental results shown at this meeting. The former covered approaches to the problem of confinement [2], studies of vector meson production from gauge/gravity duality [3], phenomenological models of hadroproduction in DIS [4], the use of lattice QCD to calculate the large-energy behaviour of total hadronic cross sections [5], lattice studies of semileptonic $B \to D^{(*,**)}$ decays, and predictions for the rare decays $\tau \to \nu_\tau \eta P$ ($P = \pi, K$) [8]. The latter reviewed data on multiparticle production at the B factories [6], diffractive phenomena at HERA [7], low-energy cross sections for $e^+e^- \to$hadrons [16] and a broad range of studies of production [9], spectroscopy and decay form factors of heavy hadrons [10,11,12,13,14].

The latest analyses of low energy hadronic cross sections in e^+e^- collisions in BaBar and KLOE[16] greatly improved the accuracy of the theoretical predictions for the anomalous magnetic moment of the muon, $(g-2)_\mu$, confirming a discrepancy with the experimental data at a level in excess of 3σ.

Recent measurements of open heavy quark production [9] confirm the good agreement with theory. In the case of quarkonium [9], on the other hand, the situation is still rather opaque. Non-relativistic QCD (NRQCD) gives overall a good description of production cross sections [15]. However, this is the result of combining a large number of independent production channels, mediated by different states in the NRQCD expansion over color and quark velocity in the meson CM frame. Each production channel has at least one overall parameter, namely a non-perturbative matrix element, to be fitted on data. Since various channels have different p_T shapes, one can fit almost every p_T distribution, and several equally good fits can be obtained. Thus, even though by now most relevant channels have been evaluated to NLO in QCD [15], the situation is still rather unsatisfactory. In addition, no choice of parameters compatible with the cross section measurements seems to allow a good description of the experimnetal data on charmonium polarization [15]. Having followed the development of this field for several years, I start being skeptical about the possibility to ever make solid theoretical predictions, at least for charmonium!

Hadronic spectroscopy is still a fascinating laboratory to explore the manifestations of confinement and test the theoretical models of bound-state formation, as confirmed by the continued interest by some among the deepest thinkers of our times [17,18]. The latest inputs in this field are emerging from the study of hadrons containing heavy quark-antiquark pairs. LHCb [12] determined the quantum numbers of the $X(3872)$, obtaining $J^{PC} = 1^{++}$, consistent with both the tetraquark ($qc\bar{q}\bar{c}$) and the molecular ($D^0 D^{*0}$) interpretation, but not with being a charmonium D-wave. Belle [13], on the other hand, reported the lack of evidence for charged or CP-odd partners of the $X(3872)$, states that are expected in the tetraquark case [a]. Further support of the molecular interpretation of these exotic states came from the observation of BB^* and B^*B^* decays of the $Z_b^+(10610)$ and $Z_b^+(10650)$ states. Finally, new clues on the origin of the $X(3872)$ were reported in the CMS study of its prompt and non-prompt production rates [9]: on one side, the prompt rate is almost an order of magnitude smaller than what predicted at leading order (LO) in non-relativistic QCD; on the other, the fraction of $X(3872)$ from B decays does not show a p_T dependence, contrary to the steep rise observed in typical charmonium states. The interpretation of these results is still lacking, as is an overall coherent picture of the nature of these states. I am fascinated by these puzzles, and look forward to the evolution of this challenge for QCD theory.

[a] Following the meeting, however, evidence for a charged state at $\sim$ 3900 MeV was presented by BES [19] and Belle [20].

3 Heavy ions

We have seen spectacular results: it's mind boggling that we can create such complex phenomena and explore their underlying dynamics [21]! The study of soft probes (e.g. inclusive multiplicities, flow) is complemented by the observation of a rich spectrum of hard probes (jets, photons and Z bosons, heavy quarks). These two classes of phenomena, once complementary, are now integrated in a single overall picture, which more and more relies on a common first-principle understanding of the underlying dynamics. Soft-probe observables are now used to examine in greater detail hard-probe processes (see e.g. the study of elliptic flow in heavy-quark final states). The simplicity and elegance of the phenomenology emerging from the measurements of hard probes is accompanied both by successful agreement with theoretical predictions, and by challenging puzzles. The field is thus widely open to major progress, coming from higher-precision studies and from measurements of new classes of observables, which will become available with higher luminosity.

The early dramatic evidence of jet quenching, observed in the first HI run of the LHC, is now accompanied by detailed quantitative studies of several new observables [23,24,25] and by continued theoretical scrutiny[26]. The measurement of prompt photons and Z^0 bosons up to $p_T \sim 200$ GeV shows rates that scale linearly with the number of participants, confirming a lack of interaction of these EW probes with the plasma. The unbalance in momentum of the recoiling jet, on the other hand, fully confirms the observation of quenching in inclusive jets. The fragmentation functions of these jets are being studied [24], as a function of event centrality, and show the expected softening [26]. The comparison of these observables across different samples (γ/Z+jet, jets) will allow studies of quark vs gluon quenching. In parallel, the measurement of charm and bottom production, as a function of p_T, shows the first weak evidence of the anticipated hierarchy in the nuclear modification factor, namely a reduced level of quenching for heavy quarks [27]. On the other hand, jets including a b quark appear to be quenched like light jets [25].

A new element emerging from the LHC data is the similarity between phenomena occurring in AA collisions [28] and features of large-multiplicity final states in pp and pA (e.g. the "ridge"): this is suggestive of a new picture of the underlying structure of the proton at very small x [29]. The modeling of the "soft" component of inclusive pp collisions is usually based on the picture of multiple collisions of parton pairs. Various degrees of correlations are required to fit the data (e.g. colour correlations, impact-parameter correlations of the partonic densities), and can be modeled with suitable parameters in the standard Pythia, Herwig or Sherpa MC generators. To which extent is this phenomenological modeling sufficient to capture the complexity of the highest-multiplicity final states? Is there some deeper multi-body dynamics (like the colour-glass model) that underlies these phenomena, both in pp and in pA/AA, and which would allow a more physics-driven parameterization of the event generators? A rich programme of exploration is now made possible by the variety of available data, with different beam types, from RHIC and LHC.

The behaviour of quarkonium in the QGP remains an exciting and prone-to-surprises playground. The LHC data [24,25,27] show a reduced amount of charmonium suppression, relative to RHIC [30]. This observation was anticipated as a possible manifestation of regeneration, namely the recombination of charm and anticharm quarks produced in the collision of different nucleon pairs. The recombination rate grows like the square of the average charm multiplicity, and is indeed expected to become numerically relevant at the LHC energy. Large cold-nuclear effects observed in dA at RHIC [30], however, could undermine this interpretation. Further tests of the kinematical dependence of charmonium suppression, and the study of charmonium production in pA at the LHC, will thus be needed to confirm regeneration.

Finally, we were reminded [31] of the versatility of HI collisions. For example, the high-intensity EM fields that are generated during the approach of such high-Z objects create a unique environment for the study of hard $\gamma\gamma$ and γg collisions.

4 Precision QCD in hadronic collisions

Hadron colliders have delivered precision measurements for a long time. Most notably the mass of the W and of the top, and various properties of charm and beauty hadrons (mixing, spectroscopy, decays). The interpretation and use of cross-sections, on the other hand, has typically suffered from large theoretical and experimental systematics (with notable exceptions, like the production rates and asymmetry of W bosons at the Tevatron, which have given valuable input for the extraction of the quark densities).

Great progress has taken place over the last few years, and is now delivering its fruits, with implications not only for the basic understanding of the proton structure and of QCD properties, but also for our ability to explore possible BSM phenomena.

The improved determination of PDFs is made possible by powerful and flexible global fitting tools [32], which can now account for and include LHC data. Direct use of LHC data offers many advantages: on one side they cover wide ranges of x at the large values of Q that are of interest for most applications. On the other, the statistical and systematic accuracy is often at the percent level. Furthermore, the data taken at different CM enegies provide further opportunities to control systematic errors and improve the precision [33]. The overall experimental precision achieved with measurements of gauge bosons [34,35], of jets [33,36] and of photons [37] starts challenging the theoretical accuracy. The report [38] of the first partial results (for the gg initial state channel) for the next-to-next-to-leading order (NNLO) jet cross section is therefore particularly timely! The scale variation is reduced to a few percent, in presence of a rate increase of about 20% relative to the NLO result. The completion of this calculation will strengthen the program of extraction of PDF densities from the LHC data, and improve the already remarkable precision obtained in the extraction of α_s from jet data [33,36]. At this level of precision, however, it is necessary to understand the impact of the complete shower evolution of (N)NLO, parton-level results on the resulting predictions for jet cross sections. Current indications [39,33] are that these effects are significant, and lead to differences with respect to the parton-level results that are as large as the scale or PDF systematics. A clarification of the origin of these effects will be necessary to fully benefit from the intrinsic accuracy of the jet cross section result that are becoming available.

At the LHC, large cross sections and the kinematical access to extended domains of phase space enable very sensitive tests of the theoretical modeling of complex final states. Recent progress in this area reported at this meeting includes: new tools for the automatic calculation ofNLO corrections to multibody final states [40,41]; estimates of the NNLO corrections to processes with very large NLO K factors [42]; new tools aiming at an improved next-to-leading-logarithmic accuracy in the description of the shower, with application to W+jet production [43]; new tools to exploit event shapes in hadronic collisions, reducing the impact of large pile-up [44]; the inclusion of multiple jet emission and resummation of Sudakov effects in the production of BSM particles, enabling a more realistic description of their final states [45,41]. Overall, there is an excellent agreement between theoretical predictions and data for a large variety of complex final states such as multijet topologies [33,36], associated production of W/Z plus jets and heavy quarks [34], vector boson pairs [46]. Some residual issue is still left in the case of associated production of W and heavy quarks, although the early large discrepancy observed by CDF is now significantly reduced in the latest Tevatron and LHC measurements [34].

The overall success of theoretical calculations in describing the fine details of complex hadronic final states encourages their use to design new strategies and propose new observables, possibly sensitive to new physics. We saw, for example, interesting new ideas, based on the use of jet masses instead of the usual H_T, to separate the QCD background from BSM multijet final states [47].

Last but not least, the large statistics of top quarks accumulated at the Tevatron and at the LHC are finally promoting the studies of top quarks [48,49,50,51] to the level of "high-precision" physics, with increasing sensitivity to the possible presence of BSM effects [52]. The most notable examples in the area of precision are the latest CDF/D0 combination of the top quark mass at the Tevatron[53], 173.20±0.87 GeV, and the precise cross section measurements at the LHC[50]. In the area of BSM, the foward-backward asymmetry reported by CDF and D0 remains a puzzle, which even the latest interesting measurements[48] do not seem to shed further light on.

The relevance of the new knowledge on m_{top}, in view of the new knowledge of the Higgs mass, was illustrated by the latest global fits of EW parameters[54]. If, on one side, the agreement between direct measurements of the top and W masses and the result of EW fits is remarkable, it is clear nevertheless that further improvements in precision would be extremely interesting. The knowledge of the Higgs mass, in fact, has greatly tightened the correlation between top and W masses, and a slight tension is observed, at the level of 1-2σ. An outstanding theoretical challenge is now the proper understanding of the systematics in the interpretation of the measured top mass. New studies by CMS[49] start addressing part of this issue, by monitoring the dependence of the measured top mass on the event kinematics. This probes the accuracy of the Monte Carlo event generators to model the fine details of top production and decay, including the impact of non-perturbative and hadronization effects.

5 BSM searches, and flavour physics

The search for BSM phenomena is driven by two considerations. On one side, there is clear and incontrovertible evidence for physics beyond the SM (dark matter, the baryon asymmetry of the universe, the origin of neutrino masses). On the other, the existence of a Higgs boson with features fully consistent with those anticipated by the SM gives more concreteness to the puzzle of the hierarchy, namely the naturalness of the EW scale and its stability with respect to the Planck scale. It is natural to expect that the solution to the latter problem will also include ingredients for the solution of the former ones, and most theoretical BSM theories that have been proposed do precisely this. Searches for their evidence have been ongoing for decades, and the access at the LHC to a new energy scale has offered new opportunities for discovery. At this meeting, we saw many new results, ranging from the direct searches of new particles (supersymmetric ones, new gauge interactions, new heavy quarks, Kaluza-Klein excitations, etc), to indirect evidence of new phenomena at large Q^2 (quark substructure, anomalous gauge couplings, anomalous properties of the top quark, etc), to indirect evidence at low Q^2 (rare decays or CP violation in flavour physics, anomalous magnetic moment of the muon, etc). No conclusive evidence, unfortunately, has matured as yet.

The study of the flavour sector of the SM, as an indirect probe for new phenomena, is strongly motivated theoretically[55,56,57], and accounts for a large fraction of the experimental programme at the flavour factories[58], at the Tevatron[59] and at the LHC[60,61,62]. Intriguing anomalies are present. For example recent data on e^+e^- annihilation to hadrons[16] confirm the $O(3\sigma)$ data vs theory discrepancy for $(g-2)_\mu$. The decays $B \to D^{(*)}\tau\nu$ and $B \to \tau\nu$, potentially sensitive to new physics such as charged Higgses, show some anomaly, but the overall picture is not fully consistent with a BSM interpretation either. The 4σ isospin asymmetry in $K^{(*)}\mu^+\mu^-$ decays of charged and neutral B mesons is puzzling[60,62], but no firm conclusion can be drawn, due to highly uncertain SM predictions. Earlier evidence for CP violation in D decays has weakened[11], but it still large enough to challenge the (rather uncertain) SM predictions. Several observables are nevertheless available[56] to further test the origin of this effect, should it be confirmed.

Lack of direct evidence of new particle production at the Tevatron[63] and at the LHC[64,65] is starting to question the viability of several BSM models. In particular, the parameter space of highly constrained models, such as the constrained minimal supersymmetric SM (CMSSM), is being strongly reduced. It would be a mistake, however, to draw general conclusions on these theoretical frameworks. In a theory such as supersymmetry, the existence of a large number of a-priori free parameters to describe its symmetry breaking pattern makes it impossible to make general statements. One is forced to simplify the task of the searches by selecting benchmark classes of models, parameterized by a reduced set of parameters. As the room left to these simpler classes of models gets reduced, the experimental searches start shifting to new benchmarks, whose manifestation can be more subtle and hard to detect. There is still a large room of exploration, and even more will be opened once the LHC restarts, at the higher energy. The whole picture was best summarized at the meeting by this statement[64]: "Physics beyond the SM did not show up yet. There is no need for preliminary conclusions. Lets continue our work and look were we havent looked so far". At a time when all theoretical wisdom on what lies beyond the SM seems to be challenged by the data, this sounds like a healthy pragmatic attitude.

The status of the CMSSM was reviewed [66]. In this framework, 125 GeV is a rather large value for the Higgs, and demands a heavy stop quark (in the TeV range), with a large mixing among the scalar partners of the left- and right-handed top quark, and a large overall mass scale for the squarks of the first two generations. Furthermore, the direct constraints on the gluino mass, setting it well above the TeV, imply large neutralino masses, and a limited range allowed for it to be the dark matter particle. Global fits, including direct limits as well as low-energy phenomenology (flavour physics) and dark matter, call for multi-TeV squarks and gluons, and for neutralino dark matter in the few-hundred to TeV range, accessible nevertheless to ton-scale detectors.

While the CMSSM is therefore still alive, I think it is fair to state that is has almost exhausted its value as a reference benchmark for direct searches. Less constrained (or otherwise constrained) supersymmetric models can easily loosen the constraints from DM and from the Higgs. There is therefore a strong motivation in exploring possible supersymmetric signals from models other than the CMSSM, as is being done with great investment of efforts and ingenuity by the LHC experiments.

6 Status of EWSB

The key questions raised at the time of the meeting concerned the real nature of the $\sim$ 126 GeV resonance: is it *a* Higgs boson? is it *the* Higgs boson? A Higgs boson can be defined as a scalar field, whose expectation value breaks spontaneously the $SU(2) \times U(1)$ symmetry. In the SM, the Higgs boson is furthermore constrained to be an elementary field (i.e. not composite), to be the member of a single $SU(2)_W$ doublet, and thus to be the only responsible for the masses of gauge bosons and of quarks and leptons. The highlight of the experimental contributions on the Higgs [67] was the proof that its decay distributions largely favour its scalar nature, relative to other possibilities (e.g. pseudoscalar, or tensor). It has been remarked [41] that, when modeling the lowest-dimension effective coupling of a spin-2 state, the coupling to the quarks and gluon currents must be kept equal, to avoid a unitarity-violating and unphysical growth of the cross-section at large p_T.

While this is very valuable information, I would not consider it as a breakpoint in our assessment of the nature of the $\sim$ 126 GeV resonance. After all, the data still do not prove that this is an elementary scalar, and we do know already of many CP-even scalars, among the hadronic states, which however have nothing to do with a Higgs boson. So the "scalar-ness" of the new particle is only a piece in the whole picture. In my view the strongest evidence that this particle is a Higgs boson comes from its couplings to gauge bosons, which follow precisely the pattern dictated by EWSB. A generic gauge-invariant coupling, would not reproduce the experimental observation of the hierarchy of couplings, namely $g(H\gamma\gamma) \ll g(HWW) \sim g(HZZ)$ and $g(HZ\gamma) \ll g(HWW)$. For example, a gauge invariant coupling like the following (see e.g. [68,69] for a more exhaustive discussion):

$$\begin{aligned} L_H &= k_W\, HW^a_{\mu\nu}W_a^{\mu\nu} + k_B\, HB_{\mu\nu}B^{\mu\nu} \\ &= 2k_W\, HW^+_{\mu\nu}W^{-\mu\nu} + (k_B + k_W)\, HF_{\mu\nu}F^{\mu\nu} \end{aligned}$$

$$+ \left(k_W \frac{c_W^2}{s_W^2} + k_B \frac{s_W^2}{c_W^2}\right) HZ_{\mu\nu}Z^{\mu\nu} + \left(k_W \frac{c_W}{s_W} + k_B \frac{s_W}{c_W}\right) HF_{\mu\nu}Z^{\mu\nu} \quad (1)$$

would require $k_B \sim k_W$ at the percent level, in order to agree with the observation $B(\gamma\gamma) \sim 10^{-2}B(WW^*)$. As a result, we would have:

$$L_H = 2k_W\, HW^+_{\mu\nu}W^{-\mu\nu} + \frac{k_W}{c_W s_W} HF_{\mu\nu}Z^{\mu\nu} + \ldots \quad (2)$$

and $B(Z\gamma) = O[B(WW^*)]$, in clear contradiction with the existing limits [70] on $B(Z\gamma)$. In my view, this is the strongest experimental evidence we have that this particle is related to EWSB, and it is therefore legitimate to assume it is a Higgs boson. Alternative interpretations must explain the observed hierarchy of Higgs couplings to gauge boson pairs and, in those specific frameworks, explain what else if not this particle breaks EW symmetry, and how EW precision tests are satisfied. I am not aware of any compelling such alternative framework, and certainly none was shown at this meeting.

As the precision of the measurements improves, initial deviations of the measured branching ratios from their SM values become weaker. The residual differences of the results of ATLAS and CMS from the SM are no bigger than the differences between the results of the two experiments, and are thus diluted after a naive combination of the two sets of data. This is true, for example, of the combined ratios $\mu = (\sigma \times BR)_{exp}/(\sigma \times BR)_{SM}$, for which ATLAS reported a value of $\mu = 1.30 \pm 0.18$, and CMS $\mu = 0.88 \pm 0.21$. While we should all be patient and wait for an official combination by the experiments, I think it is safe to assume that the final average will be consistent with $\mu = 1$ within the overall uncertainty. And the same will likely be true of the rates into individual final states, as well as of the mass.

Given the large overall uncertainties, nevertheless, there is clearly room for deviations to be detected with the future studies and larger statistics. Theoretical work is therefore ongoing, to set up the appropriate formalism to parameterize and interpret possible anomalies. Many examples of this work were discussed during the meeting: tools for trustworthy generation of Higgs look-alikes [41]; parameterizations of non-SM couplings, used in fits of the current data [71], and in handy analytical formulae for rates induced by non-SM couplings [72]; discrimination between composite and elementary Higgs [73]; analysis of J^{PC} [74]; implications for 2-Higgs-doublet models [75]; flavour implications of extended Higgs sectors [76].

7 Concluding remarks

The observation of a Higgs boson opens a new era for particle physics. Its apparent consistency with the SM Higgs boson is, on one side, a remarkable confirmation of an apparently naive theoretical setup, formulated over 40 years ago, to explain the consistency of EW symmetry with the gauge boson and fermion masses. On the other, the complete lack of evidence for new physics makes more concrete and urgent the understanding of the naturalness of the EW scale, whose stability relies, in the context of the SM, on an incredible amount of fine tuning. Very precise measurements of the Higgs properties, and a continued search for signals of BSM physics, will drive our field for many years to come. Both directions will demand an increased precision in both the experimental analyses and in the theoretical tools used for their interpretation. The broad spectrum of progress on both fronts, illustrated by many contributions to this meeting, are an encouraging indication that the community is determined, ready and capable to tackle such a gigantic challenge!

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