Standard Model Physics: Summary and Outlook

With the discovery of a scalar boson, candidates for all constituents of the Standard Model have been experimentally detected. No significant deviation from the model expectations has been found by experiments over the past 30 years. Nevertheless there are several unexplained effects at the sub-nuclear and astrophysical level, which indicate existence of physics beyond the Standard Model. Precise measurements of standard processes have historically opened the road to the detection of new phenomena and new physical states: the guiding principle of Standard Model measurements should be their potential to add building blocks to our understanding of physics.

The Standard Model Working Group of What Next has reviewed the prospects for new measurements at existing and future colliders, with particular attention to the sensitivity for indirect detection of new physics and the potential to add important pieces to our global understanding of particle physics. The main measurements in key sectors are summarised below, keeping in mind that the working group considered both a 10-year timescale, roughly corresponding to the 300 fb^{-1} LHC phase, and a 20-year and even farther horizon, corresponding to the HL-LHC phase followed by new particle colliders. A somewhat more detailed perpective of the vast amount of discussions which have been taken place on the future of Standard Model physics at the LHC and beyond is given in the paper [*Eur.Phys.J.* ***C75*** *(2015) 11, 554*], and in the document [*Frascati Phys. Ser.* ***60*** *(2015) 28-57*], which summarize the working group's activities.

- **Higgs boson couplings, total width.** The measurement of properties of the newly discovered scalar boson is a major subject for the next decades. A detailed investigation of the Higgs boson couplings to elementary bosons and fermions is particularly relevant because of their sensitivity to new degrees of freedom and to non-standard mechanisms for the generation of quark and lepton masses. Given that the natural width of the Higgs boson is too narrow to be directly measured at LHC ($\sim$ 4 MeV), only coupling ratios can be determined in model independent way. Absolute couplings can be measured with a model dependent approach assuming e.g. the value predicted by Standard Model. Precisions of the order of 10% , depending on the coupling, can be attained with the first 300 fb^{-1} at LHC. These uncertainties can be reduced to 2%–5% in the High Luminosity phase. At lepton colliders, absolute measurements of the couplings are possible. Uncertainties at the 1% level are expected at ILC and well below 1% at FCC-ee.

  At LHC the natural width can be inferred from the interference of a specific decay mode. Prospects for interference measurements at HL-LHC look very promising in view of the current upper limit (22 MeV) based on Run 1 data. At ILC/FCC-ee the Higgs width can be determined by the total HZ cross section and $\sigma \times$ BR of a specific final state.

- **Higgs boson spin-parity, CP violation.** Measurements of H spin-parity and tensor structure are based on the angular analysis of decays to vector boson pairs. The presence of anomalous non-scalar components would indicate a mixed state and new physics. Very relevant measurements can be made with high statistics, as an example at HL-LHC the sensitivity for a CP-odd component in Higgs decays can be pushed below 10%.

- **Higgs boson rare production and rare decay modes.** Higgs pair production deserves special attention because of its connection with Higgs self-couplings. The search for anomalous HH production has already started, but to reach a sensitivity corresponding to the Standard Model production an integrated luminosity corresponding to the full HL-LHC phase, with the combination of several channels, is required. Several rare Higgs decay modes, such as $H \to \mu^+\mu^-$ or $H \to Z\gamma$, are sensitive to new physics. Decay modes forbidden in the Standard Model, such as lepton flavour violation decays (e.g.

$H \to \tau\mu$), can provide a clean signature of new phenomena. Again, to reach sensitivities for SM-like rates, or to probe extensively new physics models, high luminosity is required.

- **W (and Z) boson mass, electroweak couplings.** The W mass is a crucial electroweak parameter still loosely constrained by direct measurements, its uncertainty should be reduced to take full advantage of the predictive power of electroweak fits. On a 10-year time scale, W mass measurements at LHC could reach an uncertainty of ~ 5 MeV if a broad program of LHC measurements of observables sensitive to PDF is put in place. A further reduction of the uncertainty on the W mass can be reached at ILC and FCC-ee, with the potential to cross the 1 MeV barrier. With such a precision improvement of the Z mass determination from a high statistics scan at the Z pole is required. A precise measurement of another crucial parameter, $\sin^2\theta_W$, can be performed at LHC if our uncertainties on the PDF are significantly improved by means of dedicated measurements. Also in this case lepton colliders can provide a jump in precision, for both lepton and quark electroweak couplings, shedding light on the apparent discrepancy of A_{LR} / $A_{b\bar{b}}$.

- **Triple and quartic gauge couplings, vector boson scattering.** Precision measurements of triple and quartic gauge couplings are sensitive to physics beyond the Standard Model. LHC results have already reached or surpassed the sensitivity obtained at LEP, and future data can considerably improve the present sensitivity. Possible anomalies detected with the first 300 fb^{-1} at LHC can be studied with a precision of a few percent during the High Luminosity LHC phase. Another order of magnitude in sensitivity can be gained at ILC and FCC-ee. In the QGC sector, Vector Boson Scattering (VBS) is particularly relevant, because of its sensitivity to the mechanism of electroweak symmetry breaking. A precise measurement of VBS requires the integrated luminosity expected for the HL-LHC phase.

- **Top quark mass.** The top quark mass is experimentally measured at hadron colliders with a precision of $\sim 0.5\%$, however the interpretation of the measurements in terms of pole mass is still subject to many discussions. Given the importance of this parameter in electroweak fits and given its connection to the stability of the electroweak vacuum, any effort to shed light on measurement interpretations and to assess in a robust way systematic uncertainties at hadron colliders is worthwhile. Efforts in this direction have already started, with new analysis techniques, which will exploit the large top quark statistics to be collected in the next years at LHC. Nevertheless it looks very difficult to cross the ~ 0.5 GeV uncertainty barrier at hadron colliders, because the coloured nature of the top quark affects any measurement aimed at reconstructing the final state. The problem can be overcome at lepton colliders, such as ILC or FCC-ee, because the top mass can be measured in a cross section scan at the $t\bar{t}$ threshold.

- **Top quark properties.** As the top quark plays a special role in the Standard Model and in many models of new physics, the potential of LHC as a top factory must be fully exploited. Differential $t\bar{t}$ and single top production cross sections should be measured with high precision in the 300 fb^{-1} phase; the study of top production should include precise measurements of polarisation, spin correlations and charge asymmetries, because of their sensitivity to new physics. The large samples of top quarks should also be used to make precise measurements of top decays, and in particular to perform precision studies of the tWb vertex. Precision measurements in this sector require high integrated luminosity, as an example 3 ab^{-1} at HL-LHC are required to collect enough ttH statistics for a 10% measurement of the top-Higgs Yukawa coupling, while 1 ab^{-1} is required for a 4% measurement at a lepton collider running at a c.m. energy of 1 TeV.

Heavy Ions: Summary and Outlook

The working group on "Standard Model precision measurements" has addressed, among various topics, the status and future directions for precision studies of the phase diagram of strongly-interacting matter (also denoted QCD phase diagram). A summary document is presently being finalised. This research field employs collisions of heavy ions at ultra-relativistic energies. Evidence for the formation of the Quark–Gluon Plasma (QGP), a state of matter where quarks and gluons are deconfined has by now been firmly reached. In particular, the results from Pb–Pb collisions in the LHC Run-1 show that a system with an initial temperature that exceeds by more than a factor of two the critical temperature $T_c \approx 155\,(8)$ MeV for the phase transition from hadronic matter to QGP has been created. It has also been shown that such a system is opaque to hard probes (jets, heavy quarks) traversing it, and that quarkonium states are dissociated due to the screening of the colour charge in the QGP.

The experimental exploration of the QCD phase diagram will continue in two parallel directions:

High-energy experiments. At LHC and at top RHIC energy, where the high-temperature/low-baryon-density region of the phase diagram is covered, the experiments will move towards high-precision measurements, in order to constrain the properties of the QGP and determine its equation of state and characteristic parameters —namely, the temperature, the shear-viscosity-to-entropy-density ratio and the transport coefficients, as well as their time-dependence during the collision evolution. Heavy-ion collisions at the FCC could provide several opportunities to extend these studies to the highest energies.

Low-energy experiments. A second beam-energy scan at RHIC, the continuation of the SPS programme and the new experiments at the future low-energy facilities NICA and FAIR will explore the region of the phase diagram with moderate-to-high baryonic density, to search for the onset of deconfinement and for the critical endpoint. In this scope, the SPS is a unique facility, because it offers at the same time a very high interaction rate and, with a beam energy scan, a coverage of a large portion of the phase diagram.

Our present view on the future involvement of the Italian community in these studies is summarised in the following.

- The Italian community is strongly involved in the upgrade of the ALICE experiment, which will be installed during the LHC LS2 (2019–2020) in view of data-taking during Run-3 (2021–2023) and Run-4 (2026–2029), with the goal of integrating a luminosity of about 13 nb^{-1} in Pb–Pb collisions. The largely-improved tracking resolution and the foreseen increase by two orders of magnitude of the sample of minimum-bias collisions will enable a detailed characterisation of the QGP properties with new and high-precision measurements, in particular in the sectors of heavy flavour and quarkonium production. For example, novel measurements of the production and elliptic flow of charm baryons and of the low-momentum J/ψ and ψ(2S) mesons will allow us to draw firm conclusions on the recombination mechanisms of charm quarks in the QGP, while first measurements of B mesons (or their J/ψ and D decay products) down to 1–2 GeV/c with precision better than 10% will constrain the QGP transport coefficients and enable a direct comparison with lattice-QCD calculations.

- There is interest for a proposal of a new fixed-target experiment at the SPS, currently denoted NA60+. This experiment would focus on novel high-precision measurements of thermal radiation, light vector mesons and charmonia via the detection of muon pairs, in order to search for the onset of deconfinement and the restoration of chiral symmetry. The target is a measurement of the dimuon invariant-mass spectrum with a statistics 100 times larger than the current best measurement, in order to determine, for example, the thermal radiation temperature with a 1% precision. The preparation of a Letter of Intent before 2018 would be timely in view of the update of the European Strategy for Particle Physics. The construction and running of the experiment can be envisaged for the following decade.

- Further possibilities include an experiment using the LHC proton and ion beams in a fixed-target mode (AFTER) and the opportunities offered by heavy-ion collisions at the FCC-hh with both centre-of-mass energy and projected luminosity about one order of magnitude higher than at the LHC. The Italian community looks with interest at the progress of these studies.

- The Italian theory community is involved in several aspects of the study of the QCD phase diagram, from lattice-QCD simulations of the phase transition parameters and of the QGP transport coefficients to advanced hydrodynamical modelisation of the QGP expansion and heavy-quark in-medium interactions. These studies are closely linked with the aforementioned experimental approaches: they can guide the definition of new experimental programmes and relate the measurements with fundamental properites of the strongly-interacing matter and its phase structure.