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A perspective of High Energy Physics from precision measurements
La physique des Hautes Energies du point de vue des mesures de précision

A general perspective about high energy physics

Une perspective générale pour la physique des particules

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Abstract. This volume of Compte-Rendus proposes a discussion of an ensemble of precision measurements in particle physics. It provides an experimental state of the art review as well as perspectives for future measurements. We explore in this rapid overview the pillars of our knowledge, how they were established and draw some perspectives about the necessity of a new precision era to tackle the outstanding questions of the field.

Résumé. Ce dossier des Compte-Rendus de l'Académie des Sciences rassemble huit articles qui traitent chacun d'un thème de la physique des particules. Elle présente un état de l'art des mesures et des idées qui gouvernent aujourd'hui notre représentation physique de l'infiniment petit. Elle interroge aussi les perspectives du champ au travers des mesures de précision. Nous discutons dans cette introduction rapide les fondations de nos connaissances et comment une nouvelle ère de précision peut répondre aux questions fondamentales de la physique des particules moderne.

Keywords. Precision physics, Standard model, Quarks, Leptons, Bosons, Experimental diversity, Future projects.

Mots-clés. Physique de precision, Modèle standard, Quarks, Leptons, Bosons, Diversité expérimentale, Projets futurs.

1. Precision in physics

This series of articles will simultaneously describe the state of the art of key measurements and draw some perspectives for future experimental programs. Particle physics is experiencing a change of paradigm and we start this rapid overview by highlighting inspirational examples from Physics history where precision was instrumental in overcoming the central problems of the field.

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1.1. *The tools for precision: from accelerators and detectors to theory*

Since the first Wideroe's design of a particle accelerator in 1928, the understanding of the laws of physics in the previous century has been closely entangled with the evolution in energy and beam intensity of accelerators and the development of increasingly precise particle detectors (not mentioning the computing architectures to process the data). Their review is beyond the scope of this document and the interested reader can consult [1] for a comprehensive description of the progresses in theses domains. The discovery of the Brout–Englert–Higgs (BEH) boson at the Large Hadron Collider (LHC) experiments is an exemplary illustration of the concurrent and constructive achievements in these areas. The mid-term and long term projects of particle physics, and singularly the precision measurements, are still building on the concurrent progresses in these domains.

As we will see in all the articles published after this overview, there is a continuous need to match theory precision with experimental accuracy. An enlightening illustration is the anomalous magnetic moment. The magnetic moment of an elementary particle of charge e and mass m is aligned with its spin $\vec{s}$: $\vec{\mu} = g(e/2m)\vec{s}$. In 1928, Dirac predicted that the g-factor of elementary half-spin particles, is exactly 2. This value was in agreement with the experimental knowledge at that time. However in 1947, small deviations from the expectations were seen in the hyperfine structure of hydrogen and deuterium [2,3], $a^e_{\text{exp}} = 0.00126 \pm 0.00019$ and $a^e_{\text{exp}} = 0.00131 \pm 0.00025$, respectively. In 1948 Schwinger performed calculations at the one-loop level in Quantum Electro-Dynamics (QED) leading to a small shift in g: the so-called anomalous magnetic moment, $a^e_{\text{theory}} = (g-2)/2 = \alpha/(2\pi) = 0.00116$ [4]. Nowadays the precision on the measurement of the anomalous magnetic moment of the electron has improved by 9 orders of magnitude: $a^e_{\text{exp}} = 1159652180.91(26) \times 10^{-12}$ and the theoretical prediction has undergone a similar improvement in precision: in 2012 the QED calculation at the 5-loops level, involving the evaluation of more than 12000 Feynmann graphs has been published $a^e_{\text{theory}} = 1159652181.78(77) \times 10^{-12}$ [5]. Similar parallel developments in theory and experiments have taken place for the anomalous moment of the muon. In this case, due to the larger muon mass, not only the loops involving the W and Z weak bosons have be to taken into account but also the hadronic contributions. These last ones are very difficult to compute precisely and dominate the theoretical uncertainty budget on the prediction of a_μ. The current experimental determination of $a^\mu_{\text{exp}} = 11659209.1(5.4)(3.3) \times 10^{-10}$ [1] is improved by a factor 14 with respect to the experiments from the 1970's [6]. The corresponding improvement in the theoretical prediction leads to $a^\mu_{\text{theory}} = 116591823(1)(34)(26) \times 10^{-11}$ [1], where the uncertainties are due to the electroweak, lowest-order hadronic, and higher-order hadronic contributions, respectively. There is a tension between these state-of-the-art prediction and measurement. Whether this tension is due to physics beyond what is known, overlooked uncertainties in the hadronic corrections or experimental issues, future results with increased precision will tell.

1.2. *CP-violation discovery*

Matching experimental accuracy with theory precision is necessary to produce sound tests of the theoretical predictions. Yet, there are many areas where the experimental precision is needed *per se*. Let's explore the first observation of a matter-antimatter physics difference. The first evidence of parity-symmetry (P) breaking in weak interactions [7], rapidly followed by the deeper observation that it is a maximal breaking concurrent with a maximal violation of the charge conjugation operation (C) [8], has laid the foundations of the electroweak standard model (SM) as we know it [9]. Only left-handed particles are interacting by the weak interaction. We will come back to that. It is a vibrant testimony to the necessity to experimentally test the first principles:

it then becomes clear that the laws of physics allow to make an absolute distinction between left-handed and right-handed coordinate systems, defeating the mirror reflection invariance. To overcome this intellectual discomfort, it was then advocated that the simultaneous operation of the charge conjugation and the space reflection, known as the CP transformation must be an exact symmetry of the weak interaction. In the year 1961, an experiment at the JINR Synchrophasotron [10] was conducted to search in particular for CP-symmetry breaking effects ($K_{\rm L}^0 \to \pi^+\pi^-$). The authors did not see an event out of the 255 recorded and reported a limit at 0.3%, remarkably close to the current world-average value of the branching fraction. They missed it by nothing! The decisive experiment [11] came a couple of years later at Brookhaven. Articulated with a comprehensive physics program, the primary objective of this experiment was to understand better the neutral kaon regeneration. The search for CP-violating $K_{\rm L}^0 \to \pi^+\pi^-$ was presented as a secondary target. Yet, the simultaneous characteristic of the machine intensity and the use of novel efficient spark chamber detectors made the difference to observe for the first time a CP-symmetry breaking effect. Not only the weak interaction can absolutely distinguish right from left, but particles and antiparticles have different behaviours. Incidentally, this was the first manifestation of the existence of a third generation of quarks! There are several lessons to learn from the history of this scientific revolution. Certainly, a comprehensive and well-thought physics program is a must. We are keeping for the purpose of these articles that precise instruments and large statistics are key to understanding.

2. The two pillars of the Standard Model

The Standard Model (SM) of particle physics is an elegant gauge theory able to describe (almost[1]) all particle measurements performed to date up to the electroweak energy scale. It is remarkable to note that beyond the first principles of symmetry, it built up as an intertwined evolution of experimental and theoretical progresses. The absence or the smallness of the probability of the $K_{\rm L}^0 \to \mu^+\mu^-$ decay triggered the hypothesis of the charm quark through the so-called GIM mechanism [12]; we have already discussed that the observation of CP violation introduced the possibility of three generation of quarks [13]; the B^0 meson oscillation frequency [14] and the LEP electroweak precision observables required a heavy top quark and its discovery at this very mass at Tevatron was a validation of a complete SM [15]; the same consistency test pointed towards the existence of a light BEH scalar boson that was discovered at the LHC [16, 17]. We highlight in the following the two consistency checks which constitute the modern pillars of the SM.

2.1. *The electroweak observables consistency-test*

The number of related free parameters in the SM is relatively low, in particular when focusing to the electroweak part. This is in particular due to the quadratic dependence of the radiative corrections with the fermion masses, which makes the top-quark contributions overwhelmingly dominant. Precise test of the SM can thus be performed comparing a large number of precise measurements (partial widths of the Z^0 boson, mass (m_W) and full width of the W-boson, top-quark mass (m_t), BEH-boson mass (m_H), coupling constants) with parametric SM predictions computed at the same level of precision, provided with a given set of experimental inputs (m_Z, G_F and $\alpha_{\rm EM}$). An exemplary plot is shown in Figure 1 where the W-boson mass is shown as a function of the top-quark mass. The 68% CL and 95% CL ellipses are the contours obtained from comparing the measurements with the predictions scanning the (m_t, m_W) 2D-space. The

[1]The nonvanishing masses of neutrinos are an example but would deserve a specific Compte-Rendu per se.

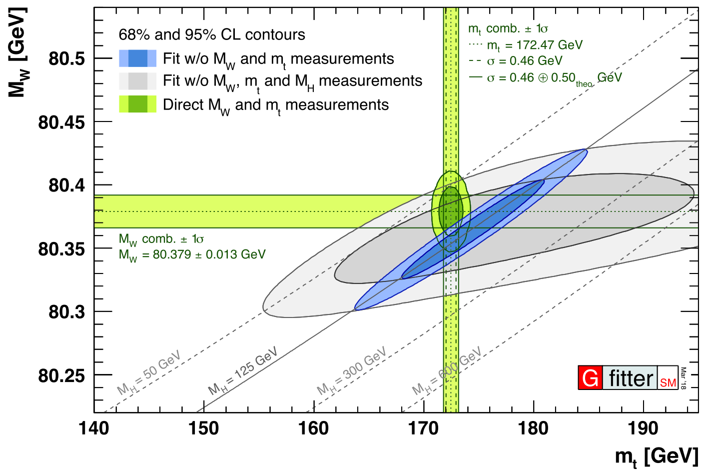

Figure 1. Contours of 68% and 95% confidence level obtained from scans of fits with fixed variable pairs m_W, m_t. The narrower blue and larger grey allowed regions are the results of the fit including and excluding the m_H measurement, respectively. The horizontal and vertical bands indicate the 1σ regions of the m_W and m_t measurements [18].

narrower blue and larger grey allowed regions are the results of the fit including and excluding the m_H measurement, respectively. The dependency of the radiative corrections with m_H is logarithmic which explains the observed milder influence. The horizontal and vertical green bands indicate the one standard deviation regions of the m_t and m_W measurements. The fact that the blue ellipse overlaps with the measurements is one of the most powerful consistency check of the SM.

2.2. *The CKM consistency check*

Another stringent test of the SM can be performed in the quark sector. The weak charged-current transitions of different generations are encoded in the Cabibbo–Kobayashi–Maskawa (CKM) matrix, which can be parameterised with four independent parameters among which one is a phase; this is in the SM the unique source of CP violation if one neglects the strong CP-phase and the neutrino masses effects. The tests consist in comparing a large number of experimental results with the corresponding predictions. Contrary to the gauge sector tests, since quarks are bounded into hadrons, an additional uncertainty comes from the estimations of the non-perturbative QCD effects that must be embodied in the fit. The set of observables considered in this global test of the SM hypothesis are selected to have clean theoretical uncertainties in their predictions and correspond to precise measurements. Remarkable progresses have been achieved in the last 20 years in the estimations of the hadronic matrix elements in particular in the framework of lattice QCD.

A graphical way to illustrate the outcome of this global fit is to represent the constraints on the ($\overline{\rho}$ and $\overline{\eta}$) 2D-space (while the SM fit has four parameters) to highlight the $\overline{\eta}$ parameter which governs the presence of CP violation in the SM. Several groups using different statistical methods [19, 20] are performing those tests and in all cases the agreement between the measurements of CP-conserving and CP-violating observables (as well as the agreement between the tree-dominated and loop-dominated constraints) allows to conclude that the KM mechanism is the dominant source of CP violation in K and B decays. In turn, beyond SM contributions are

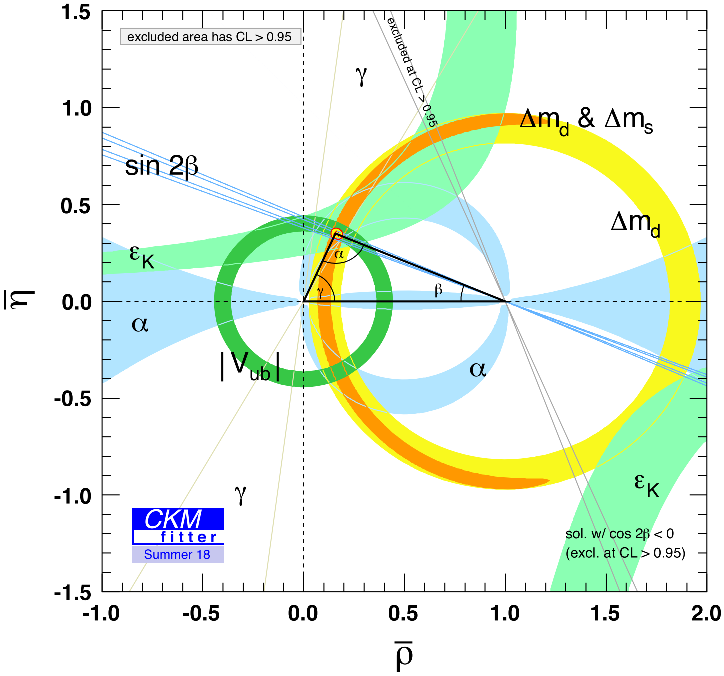

Figure 2. The consistency of the SM hypothesis is illustrated by the fact that the overlap region of the *CP*-conserving observables (V_{ub}, Δm_d and Δm_s) coincides with the overlap region of the *CP*-depending observables (α, β, γ and ϵ_K). The individual constraints are displayed for 95% C.L. exclusion. The red hashed region of the global combination corresponds to 68% C.L. exclusion.

constrained to be less than 20% as the article "*CP* violation in *B* decays" will discuss in details. An illustrative plot of the constraints on the CKM ($\overline{\rho}$ and $\overline{\eta}$) parameters is shown in Figure 2.

3. A perspective of HEP from precision measurements or precision as a perspective: finding the next energy scale

This series of articles is published at a time when a significant part of the analyses based on the LHC Run II data have been delivered. A new scalar particle consistent to date with the SM BEH boson has been discovered and no other new particle has been observed. Particle physics is therefore at a turning point of its history: there are compelling arguments that physics beyond SM must exist but we have not found a direct sign of its existence. Since there are no theoretical guidelines to infer the new physics energy scale, the balance is now towards building experimental facts.

As shown in the "Top-quark physics at the LHC" and "Higgs Physics" articles of this Compte-Rendu, the amount of produced particles already allow rather precise measurements of the heaviest fermion of the SM and of its unique spin-0 boson. In the future period of HL-LHC the precision will be dramatically increased and the results will certainly help to refine our understanding of the physics and might hopefully reveal inconsistencies. Beyond being a top quark factory, the LHC and the HL-LHC are also producing, in even larger amounts, charm and beauty quarks. For the first time, very precise measurements in this domain have been obtained at an hadronic collider. Consequently, the heavy flavour physics field is in a very healthy situation with precise information obtained in complementary experimental contexts: pp collisions at 13 TeV (LHCb, ATLAS and CMS) and e^+e^- collisions at 10.58 GeV (BaBar, Belle and Belle-II which is now starting to take data). This is highlighted in the articles on "tau and charm decays", "CP violation in B decays" and "Rare B Decays" of this issue. The latter article reports also observations of tensions with the SM predictions. None of them is significant enough to defeat the SM to date, but it is remarkable to notice that being put together, they are pointing towards a coherent beyond-SM scenario. It is thus of prime importance to collect more data in different experimental environments to clarify the picture. Furthermore detailed studies of the heaviest lepton of the SM (τ) are also pursued, mostly at e^+e^- colliders but also, for some specific modes at the LHC (see the article on "tau and charm decays").

With the discovery of a narrow scalar boson, consistent so far with the SM BEH boson, the LHC experiments have shaped an obvious case to study the properties of this particle at an equivalent precision that was achieved for the Z and W bosons at SLD, LEP and Tevatron machines. The HL-LHC facility will prolong this quest for precision and might reveal inconsistencies with the SM but there is a consensus in the particle physics community that an e^+e^- machine is in order to address comprehensively this program. Among the projects thought so far, a large scale facility of circular colliders embraces the case for precision highlighted in this series of articles. At the intensity frontier, an e^+e^- collider operated at the four electroweak energy thresholds Z, WW, ZH, $t\bar{t}$ will test the two pillars of the SM with unprecedented precision if an adequate matching of the experimental and theoretical uncertainties is achieved. At the energy frontier (>100 TeV), beyond the direct searches of new particles, a proton collider will ensure abundant production of self-coupled BEH bosons necessary to constrain the shape of the scalar potential.

A significant part of the particle physics program can only be conducted at colliders. Yet, finesse experiments, addressing the observation of forbidden or suppressed processes in the SM, that can be achieved with beam dump facilities or light flavour factories, as described in "Rare kaon decays" and "Precision experiments with muons and neutrons" are providing a complementary path to large scale collider experiments to comprehensively address the fundamental questions of the field. The selection of articles under this series of Compte-Rendu will hopefully underline the necessity and the richness of the diversity of experimental approaches.

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